KTUNOTES

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Module 2

Gate triggering circuits – R, RC, UJT triggering circuits – natural and forced commutation (concept only). Requirements of isolation and synchronization in gate drive circuits- Opto and pulse transformer based isolation.

Controlled rectifiers – half-wave controlled rectifier with R load – 1-phase fully controlled bridge rectifier with R, RL and RLE loads (continuous & discontinuous conduction) – output voltage equation – 1- phase half controlled bridge rectifier with R, RL and RLE loads – displacement power factor – distortion factor.

Gate triggering circuits

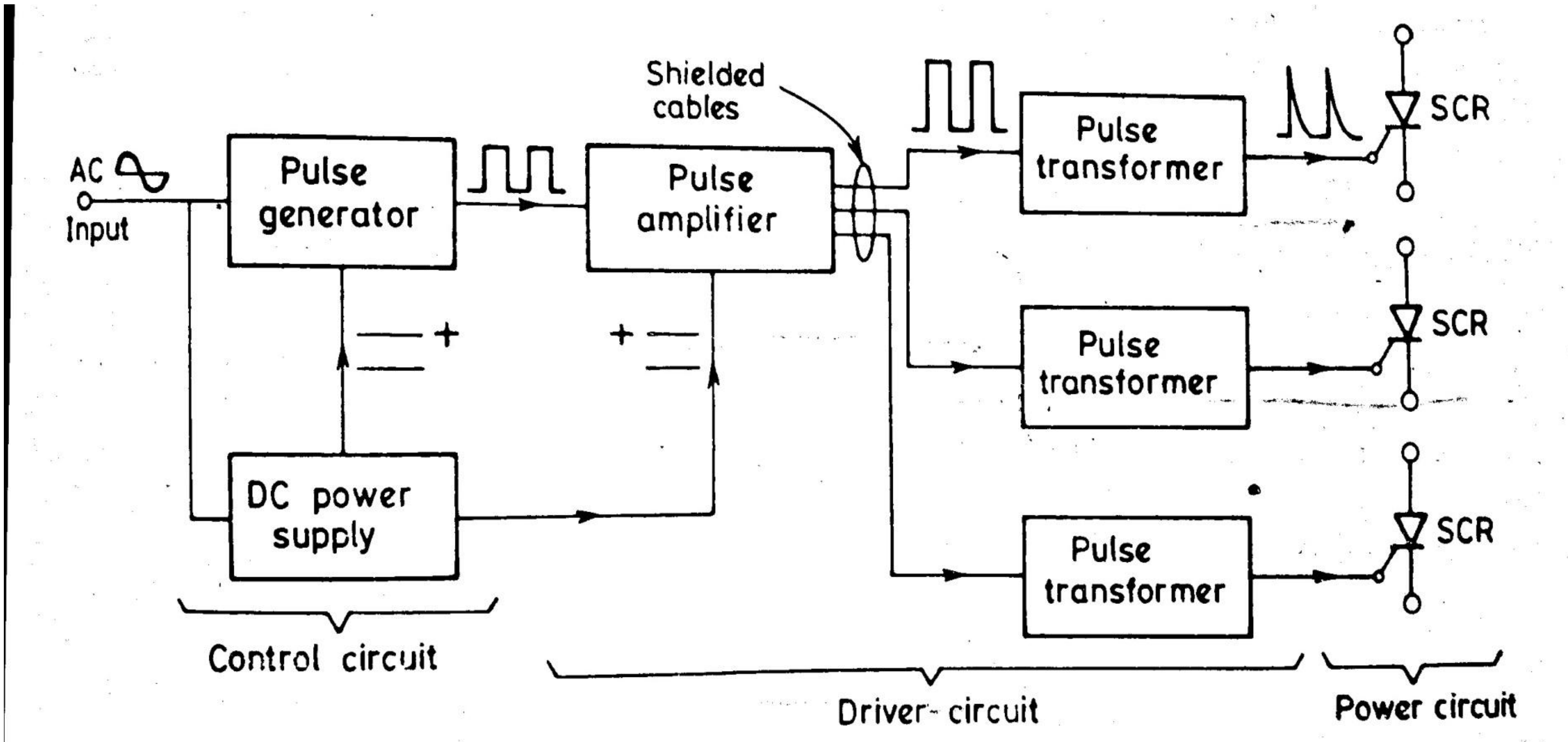
- An SCR can be switched from off-state to on-state in several ways

1. Forward voltage triggering
2. dv/dt triggering
3. Temperature triggering
4. Light triggering
5. Gate triggering

- The instant of turning on the SCR cannot be controlled by first three methods
- Light triggering used in some applications especially in series connected string
- Gate triggering – most common method, efficient and reliable

Main features of firing circuits

- Gate control circuit is also called firing or triggering circuit
- Gate circuits are usually low power electronics circuits

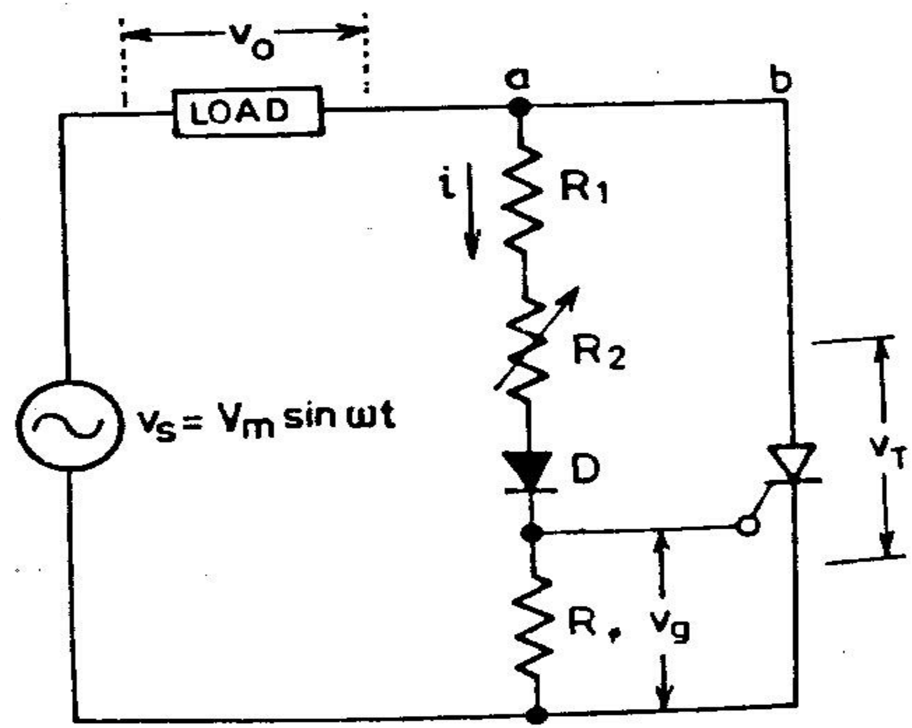


Main features of firing circuits

- A firing circuit should fulfill the following two functions
- If power circuit has more than one SCR, the firing circuit should produce gating pulses for each SCR at the desired instant for proper operation of the power circuit
- The control signal generated by a firing circuit may not be able to turn on an SCR. It is therefore common to feed the voltage pulse to a driver circuit and then to a gate cathode circuit

R triggering circuit (Resistance triggering)

- Simplest and most economical
- Suffer from a limited range of firing angle control (0 to 90°)
- R2 - variable resistance
- R – stabilizing resistance
- In case R2=0, gate current may flow from source, trough load, R1, D and gate to cathode



R triggering circuit (Resistance triggering)

- This current should not exceed maximum permissible gate current Igm
- R1 therefore found from the relation

$$\frac{V_m}{R_1} \leq I_{gm} \qquad or\ R_1 \geq \frac{V_m}{I_{gm}}$$

- Function of R1 is to limit the gate current to a safe value as R2 is varied
- Resistance R should have a value such that maximum voltage drop across it does not exceed maximum possible gate voltage Vgm

R triggering circuit (Resistance triggering)

- This can happen only when R2 is zero
- Under this condition

$$\frac{V_m}{R_1 + R} . R \leq V_{gm}$$

- As resistance R1, R2 are large, gate trigger circuit draws a small current
- Diode D allows the flow of current during positive half cycle only
- The amplitude of this dc pulse can be controlled by varying R2

R triggering circuit (Resistance triggering)

- The potentiometer setting R2 determines the gate voltage amplitude
- When R2 is large current i is small and the voltage across R,vg=i.R is also small
- As Vgp is less than Vgt, SCR will not turn on
- Therefore load voltage vo=0, io=0 and supply voltage appear across SCR
- Trigger circuit consist of resistance only, therefore vg is in phase with source voltage vs
- R2 is adjusted such that Vgp=Vgt, this gives the value of firing angle as 90

R triggering circuit (Resistance triggering)

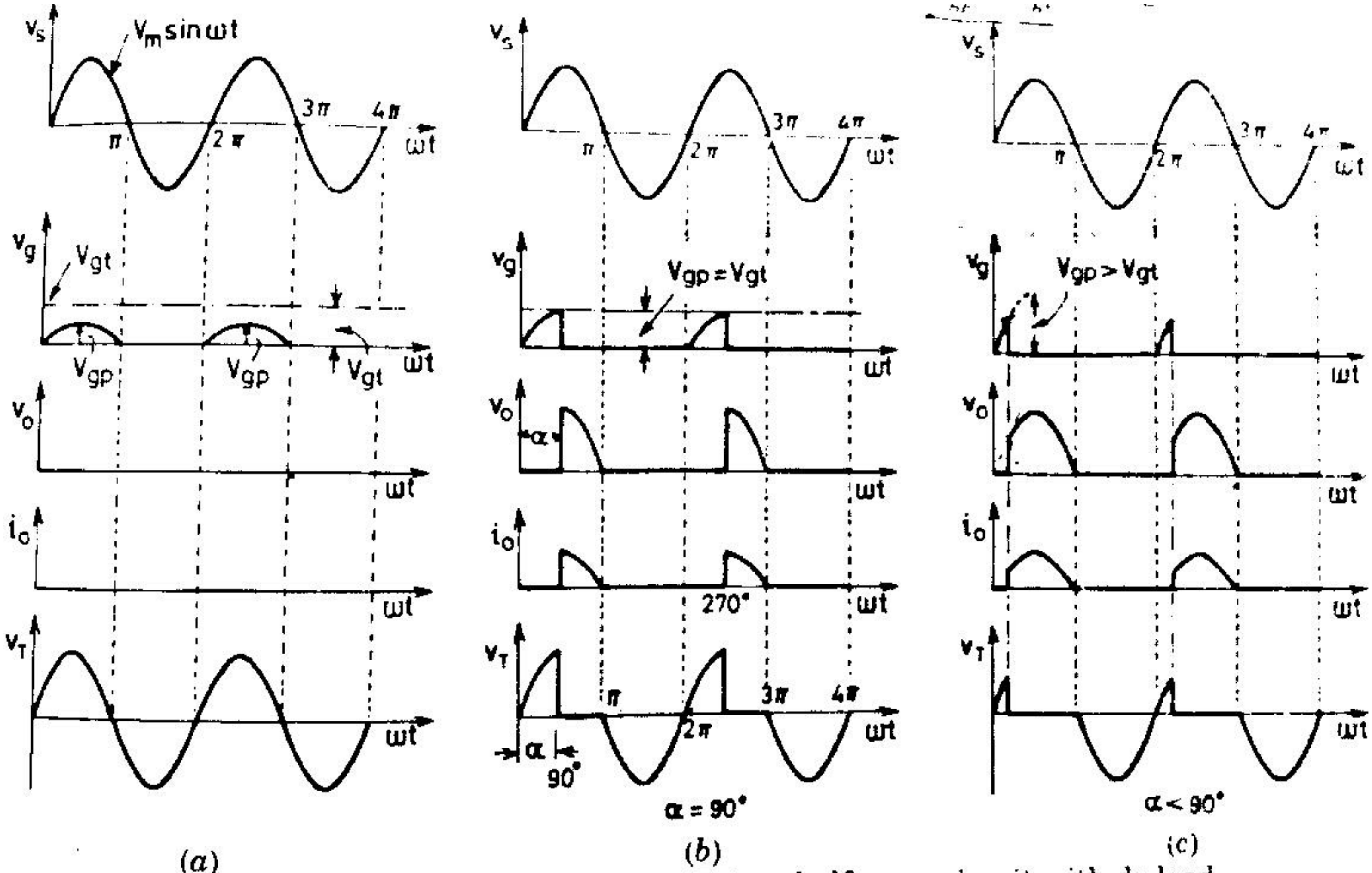


Fig. 4.65. Resistance firing of an SCR in a half-wave circuit with dc load
(a) No triggering of SCR (b) $\alpha = 90°$ (c) $\alpha < 90°$.

R triggering circuit (Resistance triggering)

- The same circuit also is applicable for TRIAC.
- However, diode D1 has to be removed such that a trigger signal will be available at the gate terminal during both half-cycles.
- Because the gate of a TRIAC is not equally sensitive in all four of its modes of switching, α and hence vo are usually different in the positive and negative half-cycles of the supply voltage.

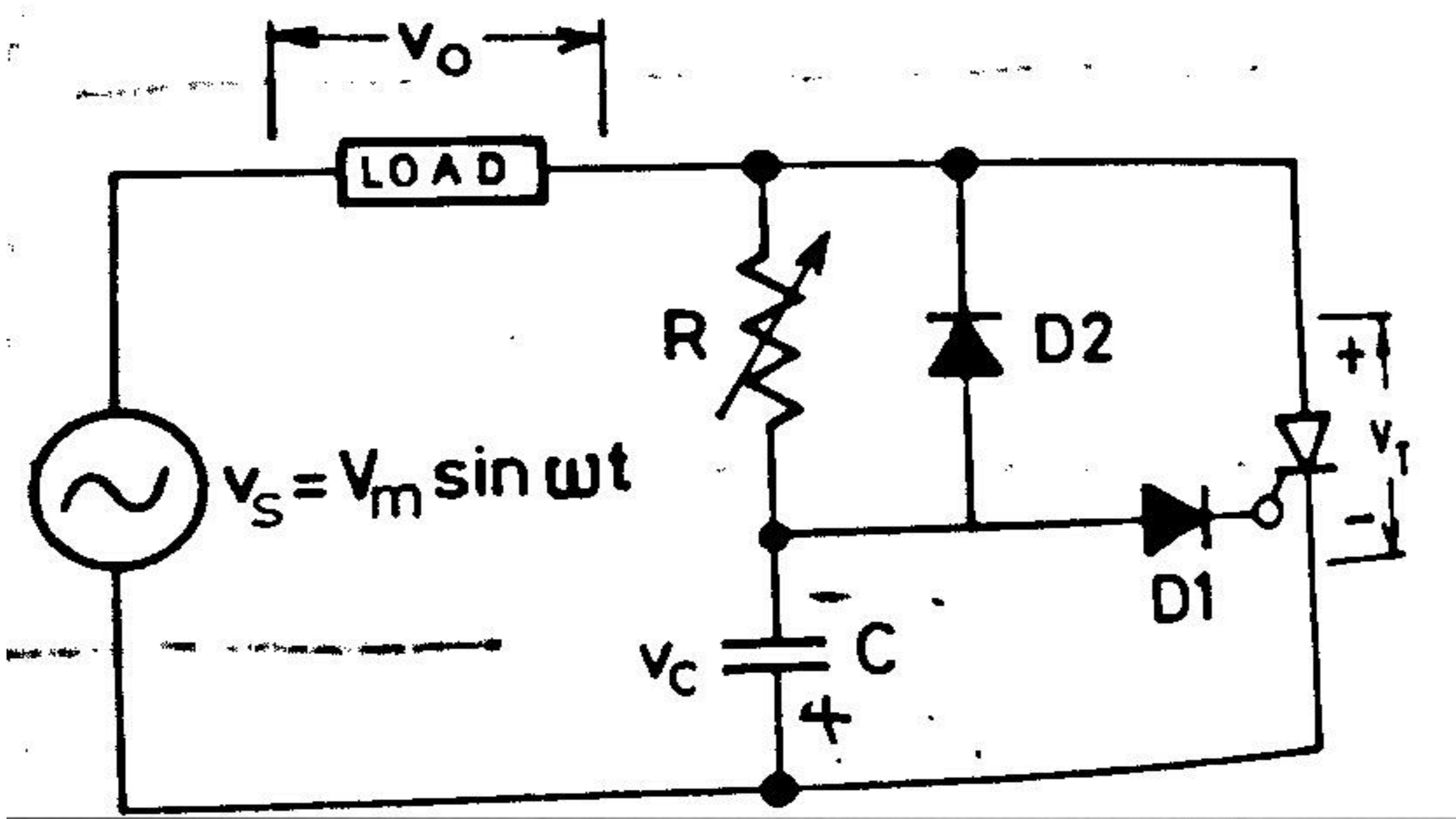
RC triggering circuit

- The limited range of firing angle control by resistance firing circuit can be overcome by RC firing circuit
- Several variations of RC trigger circuits are available
- In these cases the range of α is extendable beyond 90.

RC half wave triggering circuit

- By varying the value R, firing angle can be controlled from 0 to 180
- In the –ve half cycle capacitor C charges through D2 with lower plate +ve to the peak supply voltage Vm at $\omega t=-90$
- After $\omega t=-90$, source voltage Vs decreasing from –Vm at $\omega t=-90$ to zero at $\omega t=0$

RC triggering circuit



RC triggering circuit

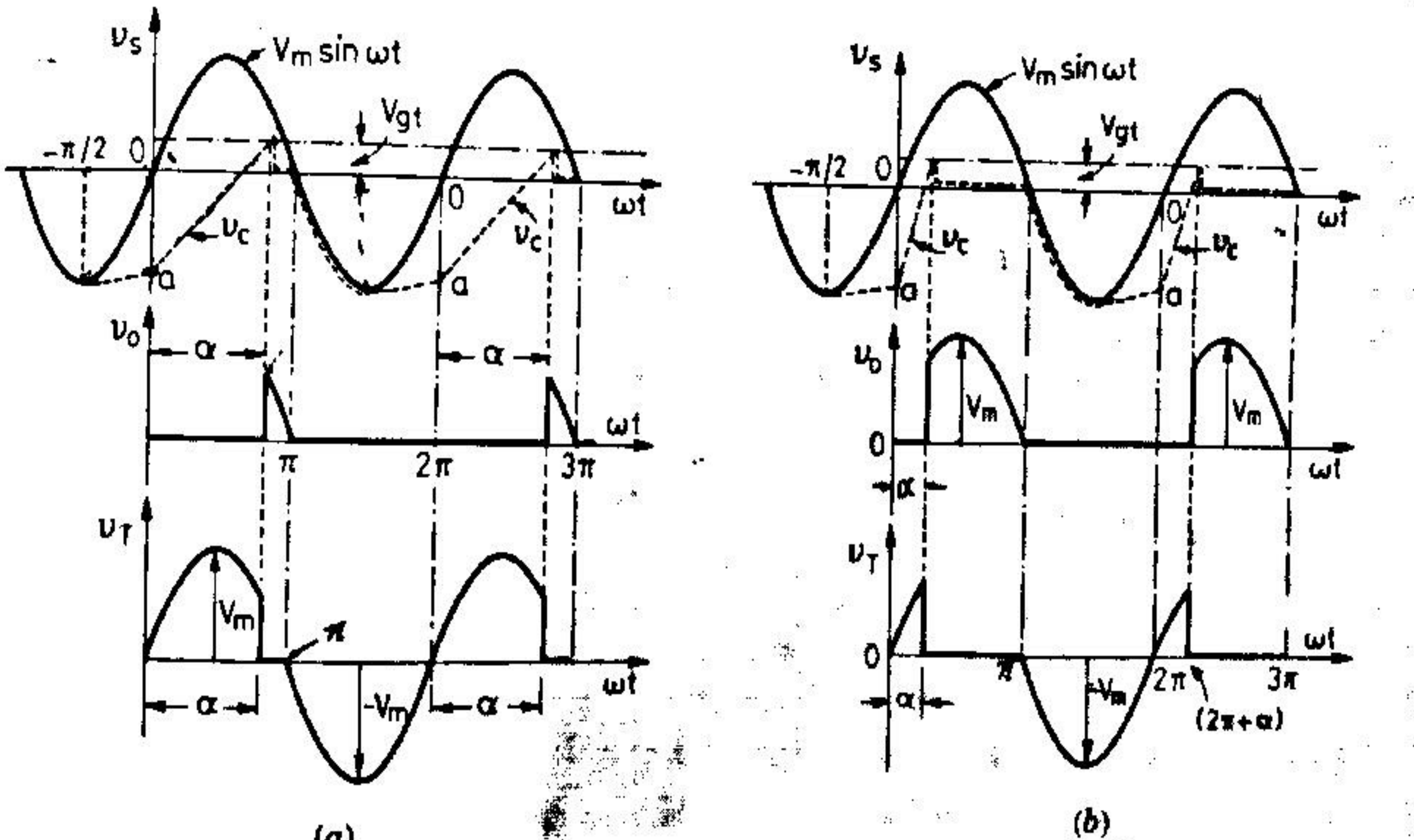


Fig. 4.67. Waveforms for RC half-wave trigger circuit of Fig. 4.66 (a) high value of R (b) low value of R.

RC triggering circuit

- During this period capacitor voltage may fall from -Vm to some small value -oa
- Now the charging of the capacitor (with upper plate positive) takes place through R and the charging rate depends on the time-period RC.
- When capacitor charges to +ve voltage equal to VGT , conduction of the SCR takes place.
- After this capacitor holds a small +ve voltage
- Diode D1 used to prevent the breakdown of cathode to gate junction through D2 during the –ve cycle

$$RC \geq 0.65T = 4/\omega$$

RC triggering circuit

- where the angular frequency of ac mains ωt= 2π/T.

$$RC \geq \frac{1.3\,T}{2} = \frac{4}{\omega}$$

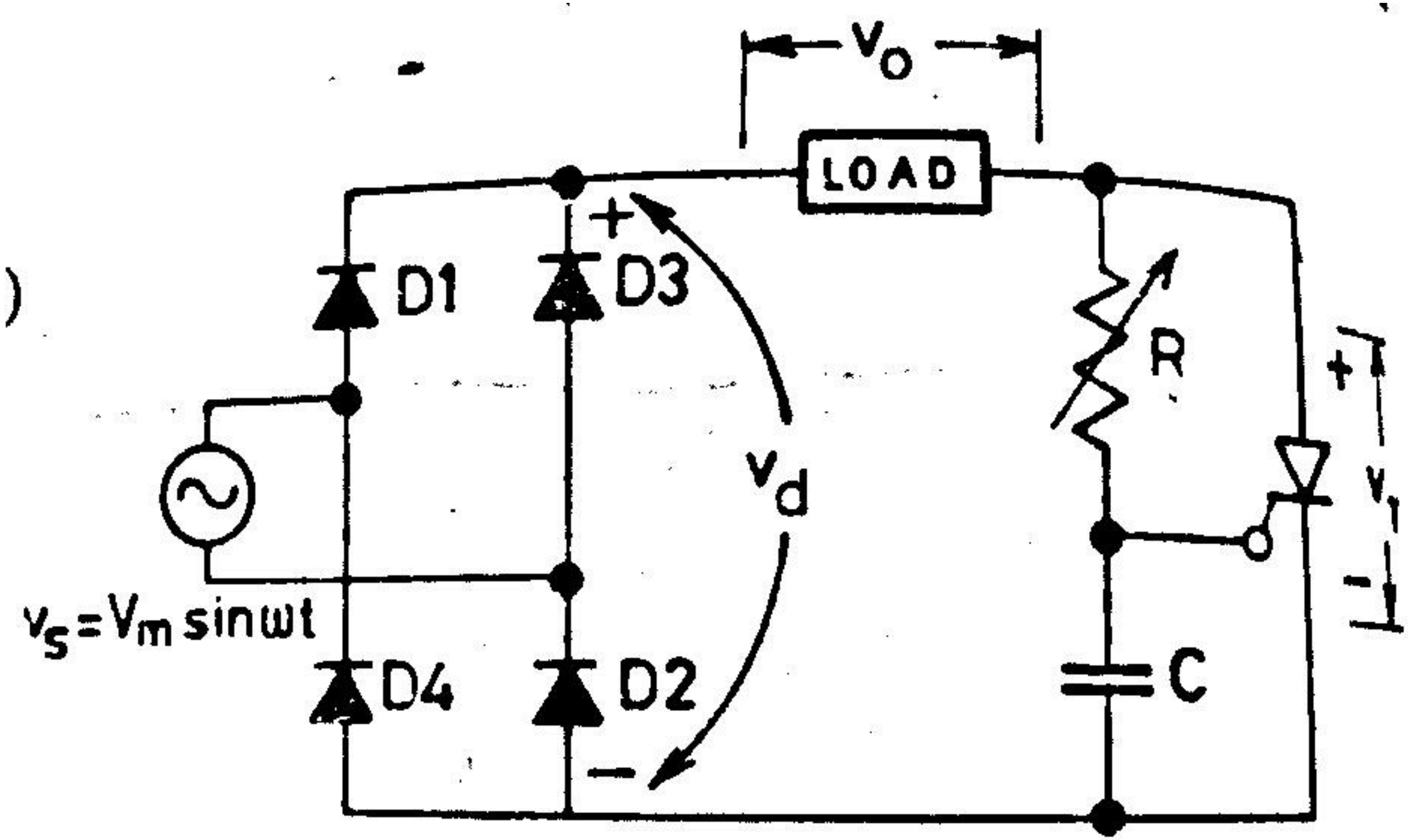
- The value of R is chosen such that the required I_{GT} and V_{GT} are supplied to the gate terminal:

$$R \leq \frac{V_s - V_{gt} - v_d}{I_{gt}}$$

- Where v is the voltage at the switching instant of thyristor and v_D is forward voltage drop of diode D1

RC triggering circuit

RC Full wave triggering circuit



RC triggering circuit

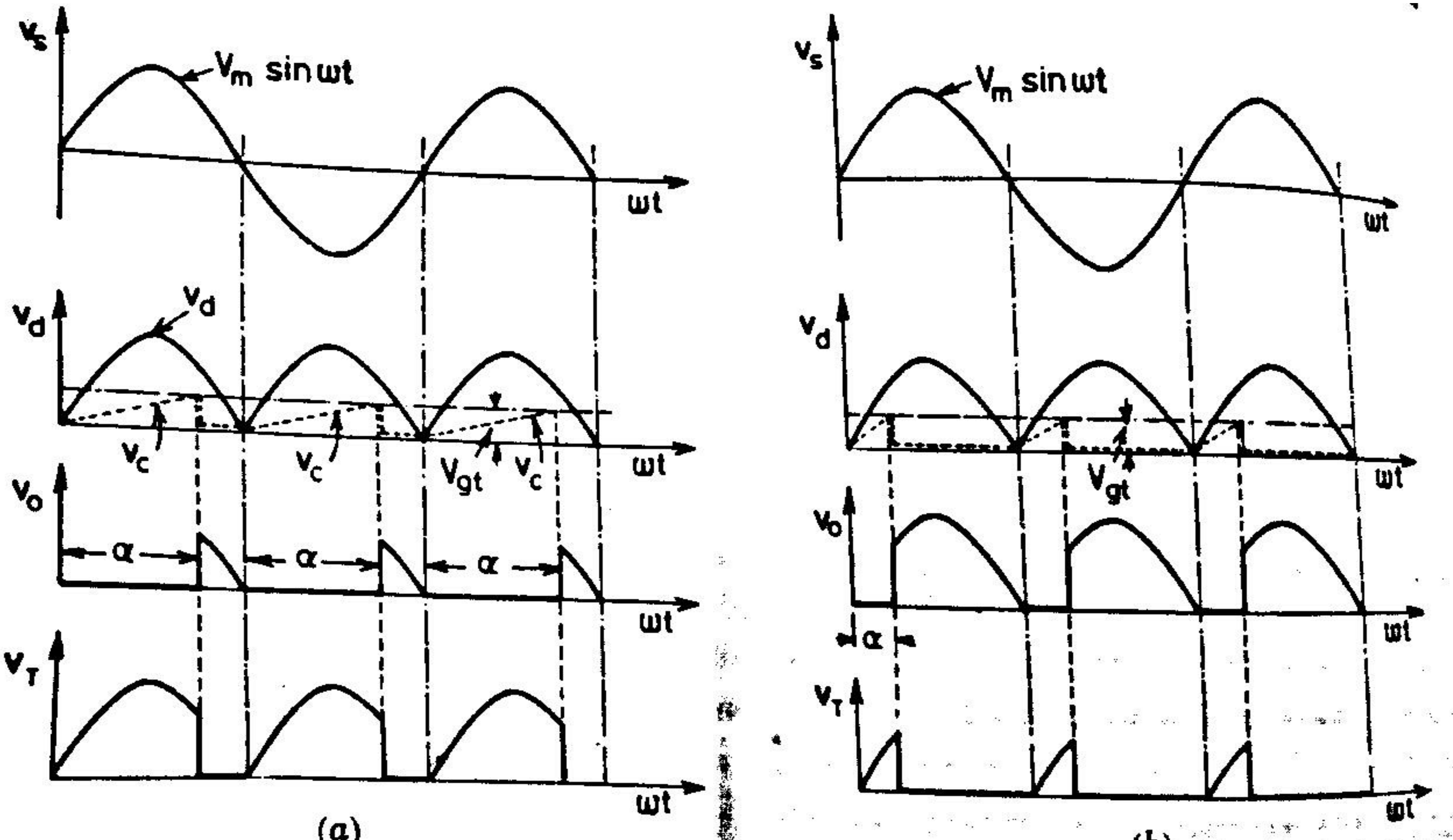


Fig. 4.69. Waveforms for RC half-wave trigger circuit of Fig. 4.68 (a) high value of R (b) low value of R.

RC triggering circuit

- Diode D1-D4 form a full – wave diode bridge
- When capacitor charges to a voltage equal to Vgt, SCR triggers and rectified voltage Vd appears across load as Vo
- The value of RC can be calculated by

$$RC \geq 50.\frac{T}{2} = \frac{157}{\omega}$$

- R is given by

$$R \ll \frac{V_s - V_{gt}}{I_{gt}}$$

UJT triggering circuit

- Resistance and RC triggering circuits described above gives prolonged pulses
- As a result power dissipation in the gate circuit is large
- At the same time, R and RC triggering circuits cannot be used for automatic or feedback control system
- These difficulties can be overcome by use of UJT triggering circuits
- An UJT is made up of an n-type silicon base to which p-type emitter is embedded
- The n-type base is slightly doped whereas p-type is heavily doped

UJT triggering circuit

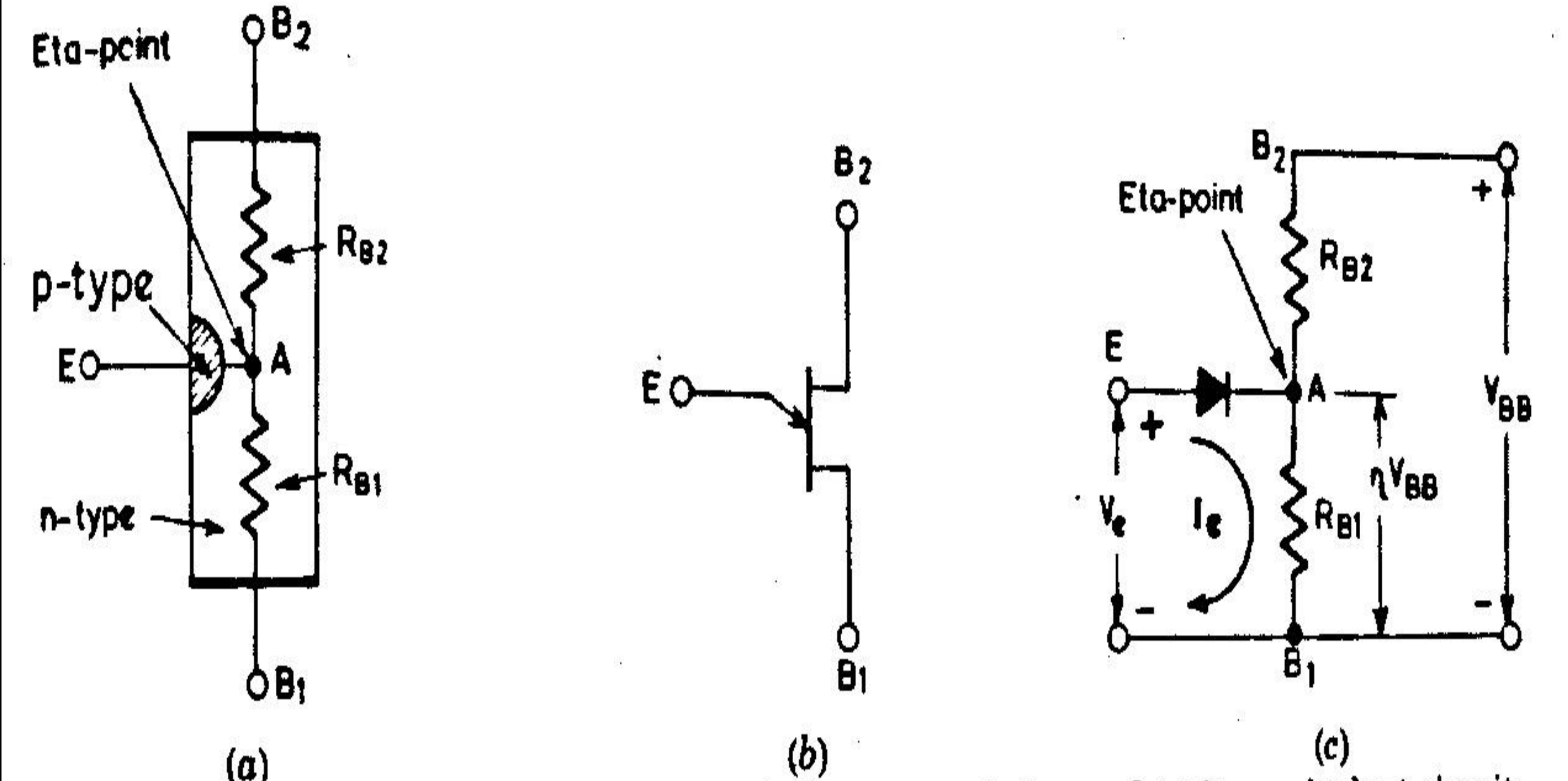


Fig. 4.70. (a) Basic structure of UJT (b) symbolic representation and (c) its equivalent circuit.

UJT triggering circuit

- The two ohmic contacts provided at each end are called base-one B1 and base-two B2
- So an UJT is a three terminal device emitter, base one and base two
- The emitter terminal divides the inter base resistance (VBB) into two parts (say, RB1 and RB2).
- If a dc biasing voltage (VBB) is applied across the base terminals, the voltage in N-type material near emitter terminal (k) is given by

$$V\eta = \frac{R_{B1}}{R_{B1} + R_{B2}} = \eta V_{BB}$$

- where η is called the intrinsic-standoff ratio of UJT and its value is less than unity (typical value varies between 0.5 and 0.85).

UJT triggering circuit

- The UJT is highly efficient switch; its switching time is in the range of nanoseconds
- Since UJT exhibit negative resistance characteristics, it can be used as a relaxation oscillator

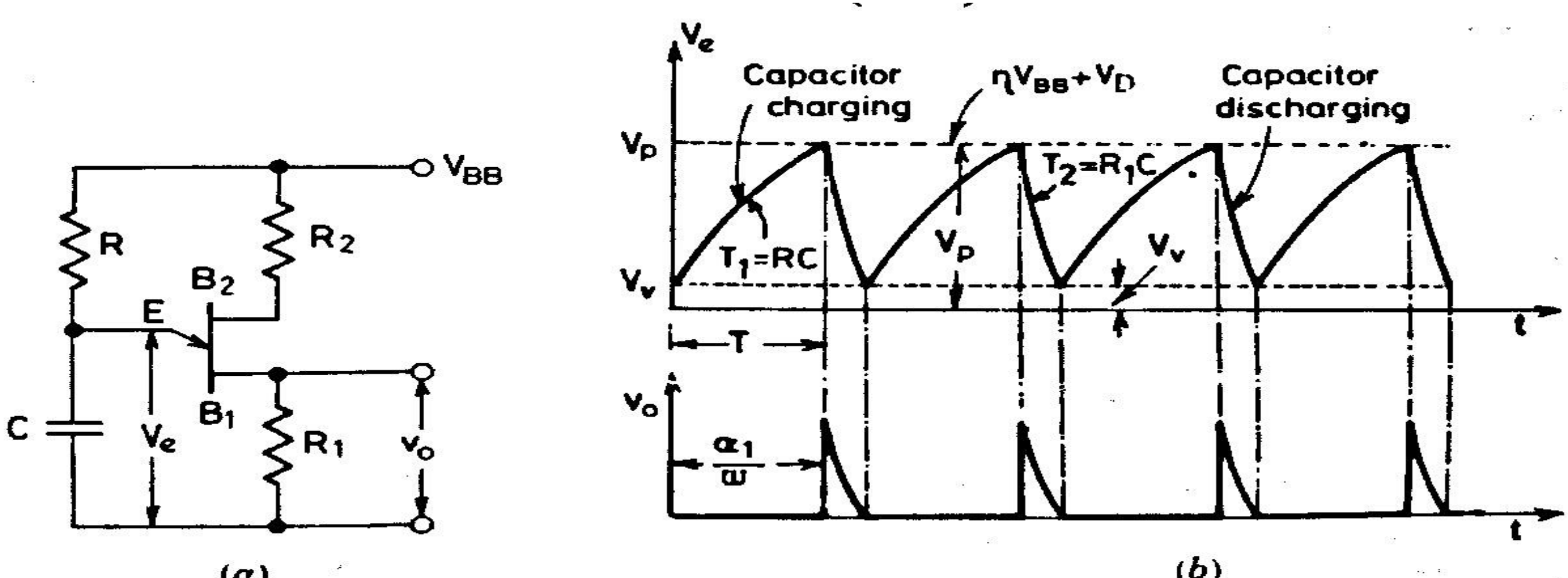


Fig. 4.72. UJT oscillator (a) Connection diagram and (b) Voltage waveforms.

UJT triggering circuit

- The external resistance R1 and R2 are small in comparison with the internal resistances RB1 and RB2
- The charging resistance R should be such that its load line intersect the device characteristics only in the –ve resistance region
- When source voltage VBB is applied, capacitor C begins to charge through R exponentially towards VBB
- The time constant of the charge circuit is

$$\tau_1 = RC$$

- When this emitter voltage reaches peak-point voltage Vp, the uni-junction between E-B1 breaks down

UJT triggering circuit

- As a result, UJT turns on and capacitor C rapidly discharges through low resistance R1 with a time constant

$$\tau_2 = R_1 C$$

- When emitter voltage decays to the valley-point voltage Vv, emitter current falls below Iv and UJT turns off
- The time T required for the capacitor C to charge from initial voltage Vv to peak-point voltage Vp through large resistance R can be obtained as

$$V_p = \eta V_{BB} + V_D = V_v + V_{BB}\left(1 - e^{-T/RC}\right)$$

UJT triggering circuit

$$V_D = V_v, \eta = \left(1 - e^{-T/RC}\right)$$

$$T = \frac{1}{f} = RC \ln\left(\frac{1}{1-\eta}\right)$$

UJT triggering circuit

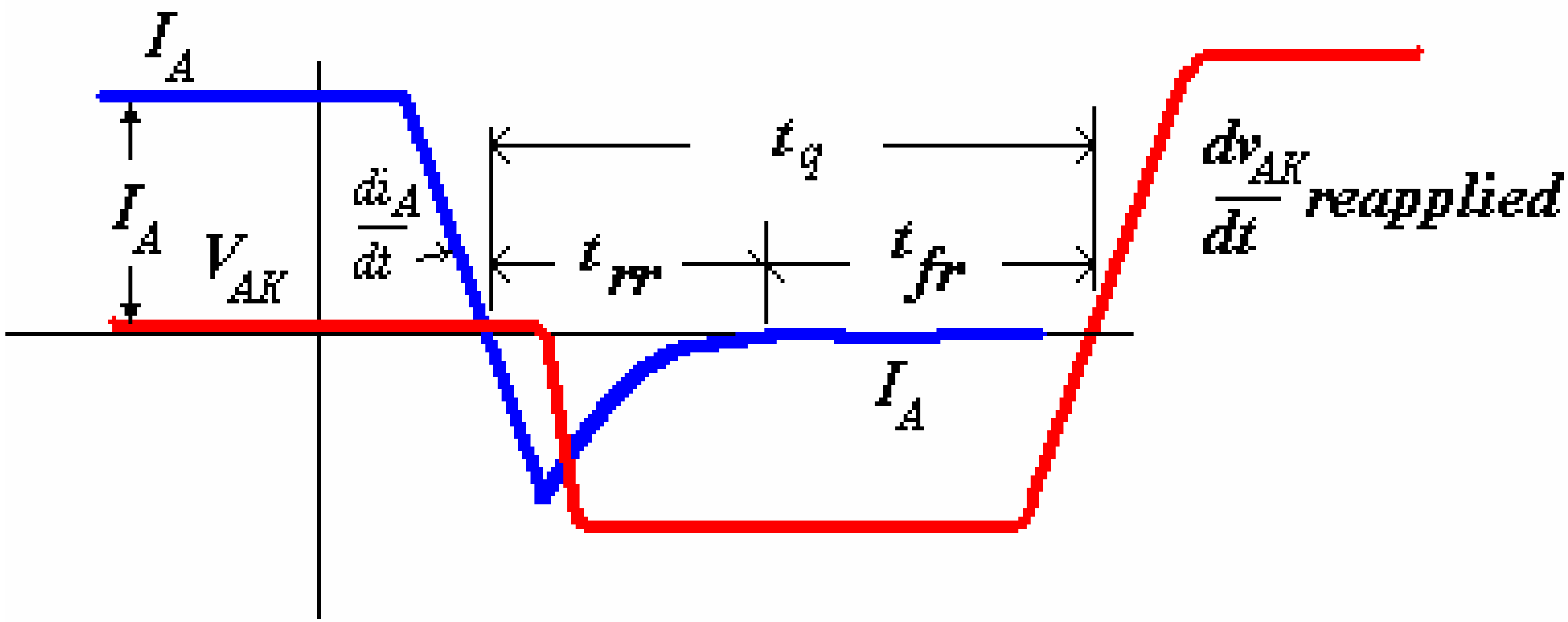
- The charging of the capacitor starts from each zero crossover instant only.
- The first pulse in each half-cycle that triggers the thyristor is synchronized with v, and therefore α becomes equal in each cycle.
- By controlling R, the time period of oscillator (τ), or the delay period of the first pulse (τ), α can be adjusted.
- The UJT trigger circuit may also be energized from a separate transformer (for biasing) and the same performance can be achieved.

Natural and forced commutation

- A thyristor can be turned ON by applying a positive voltage of about a volt or a current of a few tens of milliamps at the gate-cathode terminals.
- However, the amplifying gain of this regenerative device being in the order of the 10^8, the SCR cannot be turned OFF via the gate terminal.
- It will turn-off only after the anode current is annulled either naturally or using forced commutation techniques.
- These methods of turn-off do not refer to those cases where the anode current is gradually reduced below Holding Current level manually or through a slow process.
- Once the SCR is turned ON, it remains ON even after removal of the gate signal, as long as a minimum current, the Holding Current, Ih, is maintained in the main or rectifier circuit.

Natural and forced commutation

Turn off dynamics of SCR



Natural and forced commutation

- In all practical cases, a negative current flows through the device.
- This current returns to zero only after the reverse recovery time trr, when the SCR is said to have regained its reverse blocking capability.
- The device can block a forward voltage only after a further tfr, the forward recovery time has elapsed.
- Consequently, the SCR must continue to be reverse-biased for a minimum of tfr + trr = tq, the rated turn-off time of the device.
- The external circuit must therefore reverse bias the SCR for a time toff > tq. Subsequently, the reapplied forward biasing voltage must rise at a dv/dt < dv/dt (reapplied) rated.

Natural and forced commutation

- SCRs have turn-off times rated between 8 - 50 μsecs.
- The faster ones are popularly known as 'Inverter grade' and the slower ones as 'Converter grade' SCRs.
- The latter are available at higher current levels while the faster ones are expectedly costlier

Natural and forced commutation

The six distinct classes by which the SCR can be turned off are:

- Class A Self commutated by a resonating load
- Class B Self commutated by an L-C circuit
- Class C C or L-C switched by another load carrying SCR
- Class D C or L-C switched by an auxiliary SCR
- Class E An external pulse source for commutation
- Class F AC line commutation

Class A Commutation: Load commutation

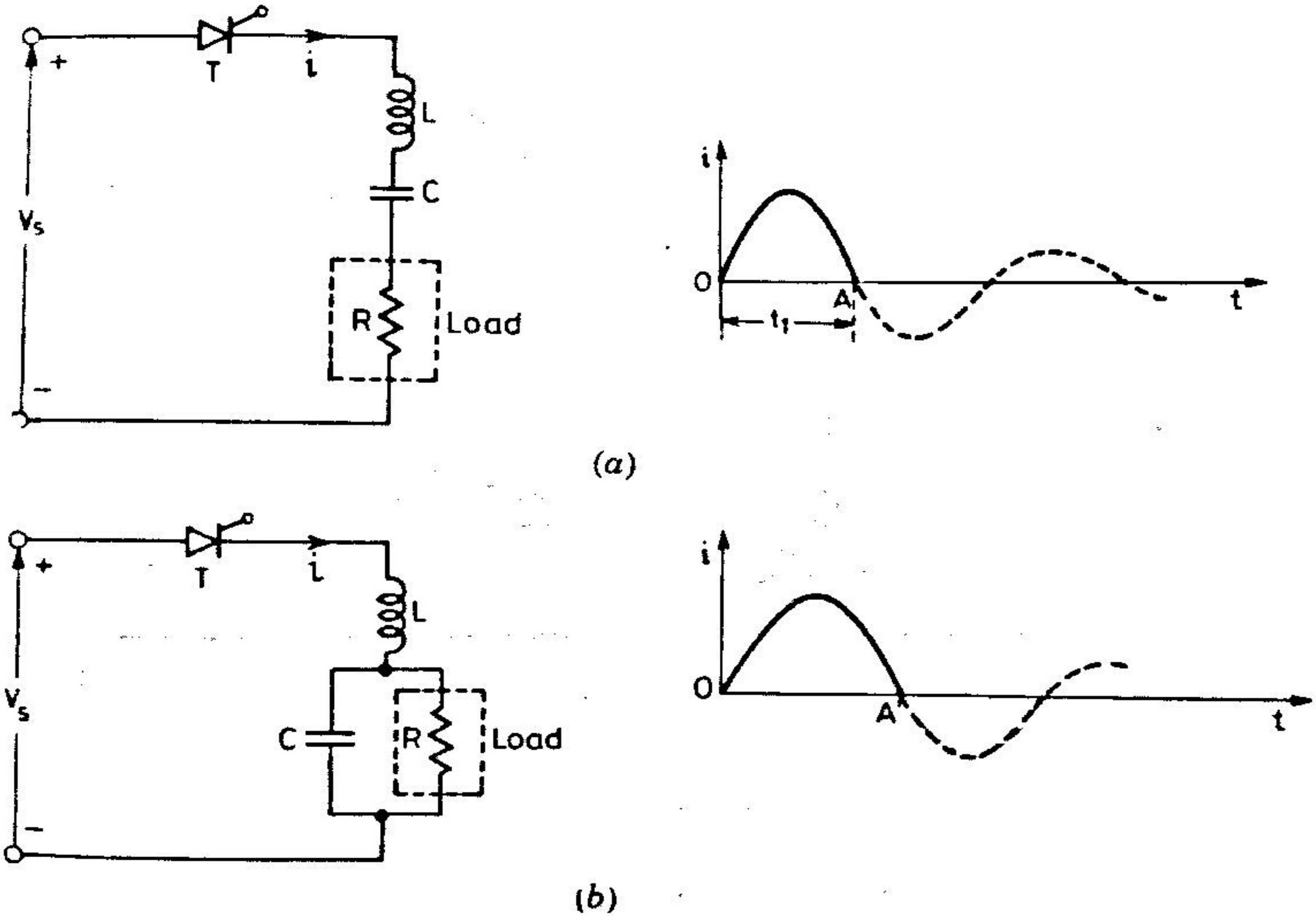


Fig. 5.1. Class A or load commutation (a) series capacitor (b) shunt capacitor.

Class A Commutation: Load commutation

- R is load resistance
- For low values of R, - R, L and C can be connected in series
- For high values of R – E and R are connected in parallel
- Essential requirement for both the circuit – overall circuit must be under-damped
- When energized from dc source, current builds up like sinusoidal wave form
- Current first rises to maximum value and then decreases
- When current decays to zero and tends to reverse, SCR T is turned off
- Possible only in dc circuit
- Also called - resonant commutation, self commutation or load commutation

Class B: Resonant pulse commutation

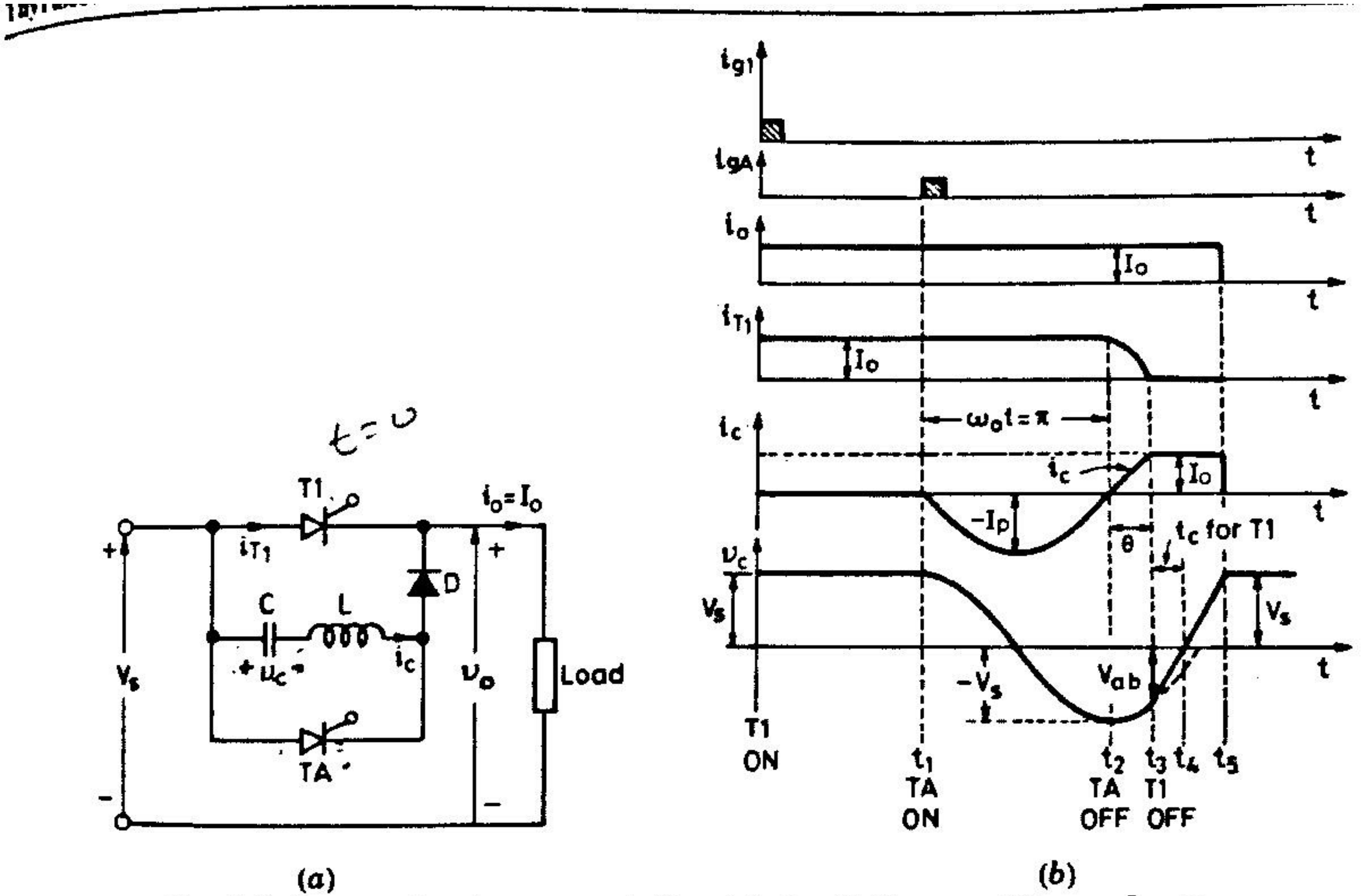


Fig. 5.3. Resonant-pulse commutation (a) circuit diagram (b) waveforms.

Class B: Resonant pulse commutation

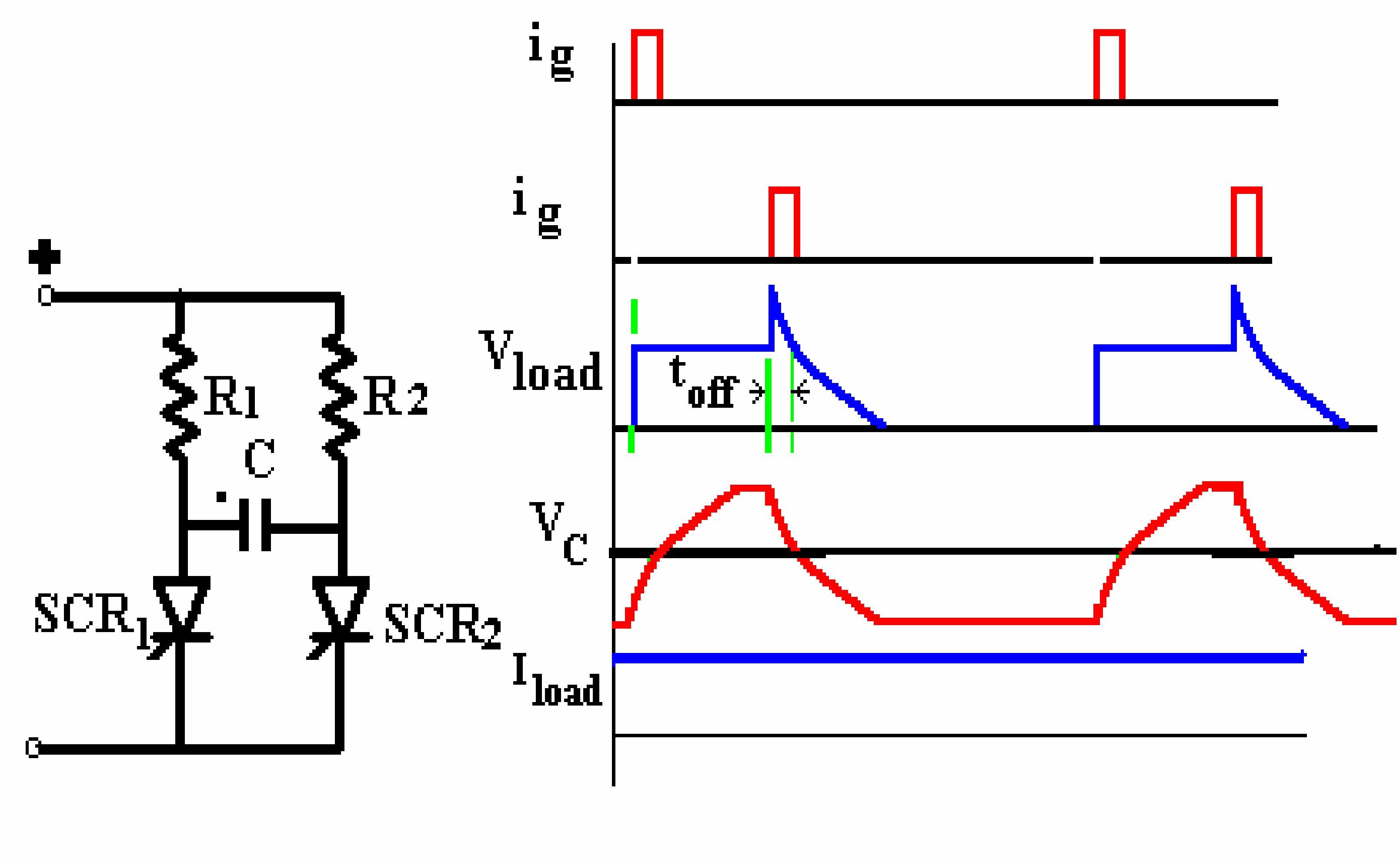
- Source voltage Vs charges capacitor C to voltage Vs with left hand plate +ve
- Main thyristor as well as auxiliary thyristor are off
- When T1 is turned on at t=0, constant current Io is is established in the load circuit
- Up till time t1; ic=0, vc=Vs,io=Io iT1=Io
- For initiating the commutation of main thyristor T1, auxiliary thyristor TA is gated at t=t1
- With TA on, a resonant current ic begins to flow from C through TA, L and back to C

Class B: Resonant pulse commutation

$$i_c = -V_s \sqrt{\frac{C}{L}} \sin \omega_0 t$$

- -ve sign is due to the fact that, this current flows opposite to the reference +ve direction chosen for ic
- At t1; ic=0, vc=-Vs and iT1=Io
- Just after t2, ic tends to reverse , TA is turned off at t2
- With vc=-Vs, right hand plate has +ve polarity
- Resonant current ic now builds up through C, L, D and T1
- As this current ic grows opposite to forward thyristor current of T1, net forward current iT1=Io-ic begins to decrease
- Finally when ic in the reversed direction attains the value Io, forward current in T1 is reduced to zero and the device T1 is turned off at t3

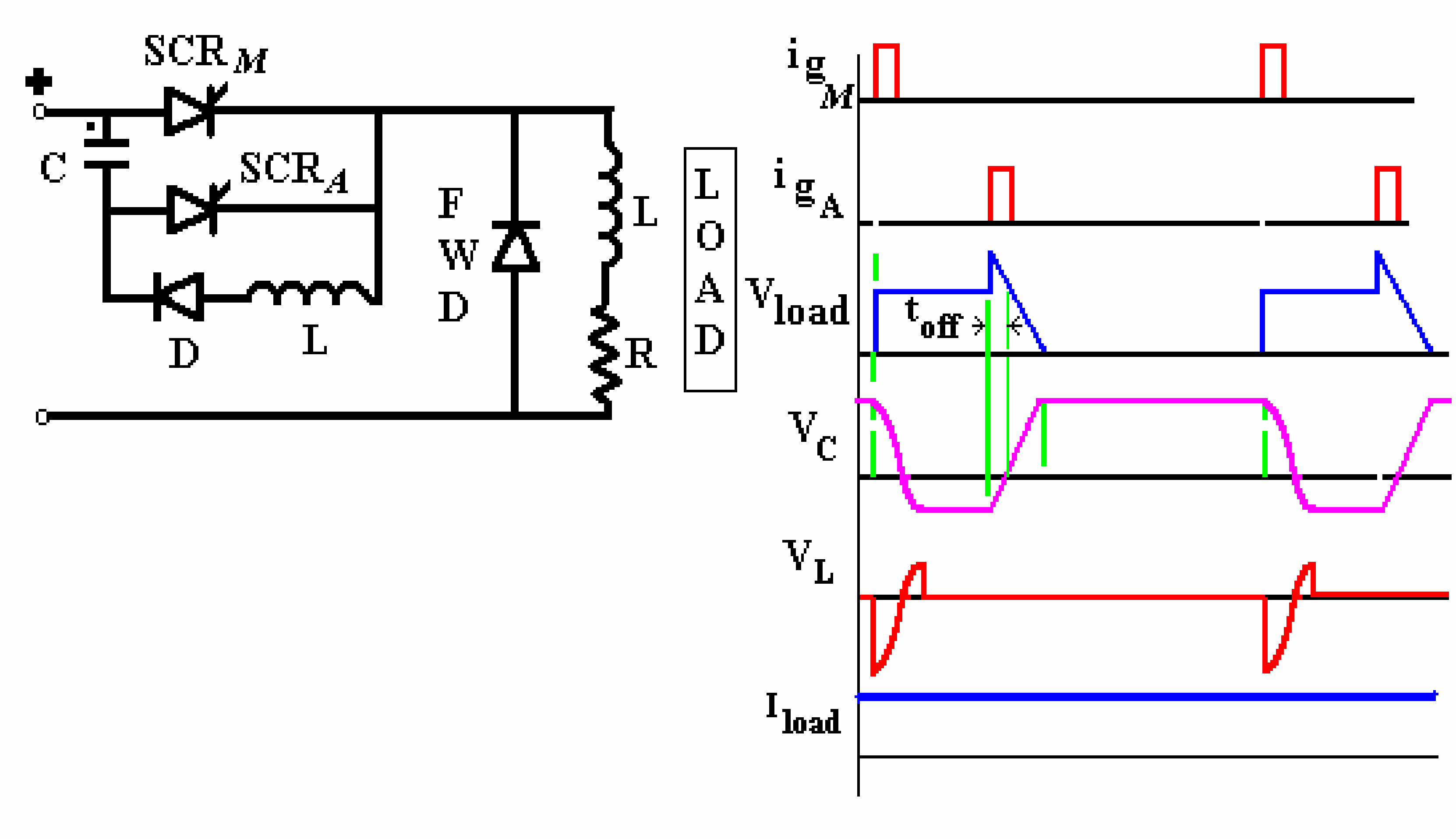
Class C, C or L-C switched by another load–carrying SCR



Class C, C or L-C switched by another load–carrying SCR

- This configuration has two SCRs.
- One of them may be the main SCR and the other auxiliary.
- Both may be load current carrying main SCRs.
- The configuration may have four SCRs with the load across the capacitor, with the integral converter supplied from a current source.
- Assume SCR^2 is conducting. C then charges up in the polarity shown.
- When SCR^1 is triggered, C is switched across SCR^2 via SCR^1 and the discharge current of C opposes the flow of load current in SCR^2.

Class D, L-C or C switched by an auxiliary SCR



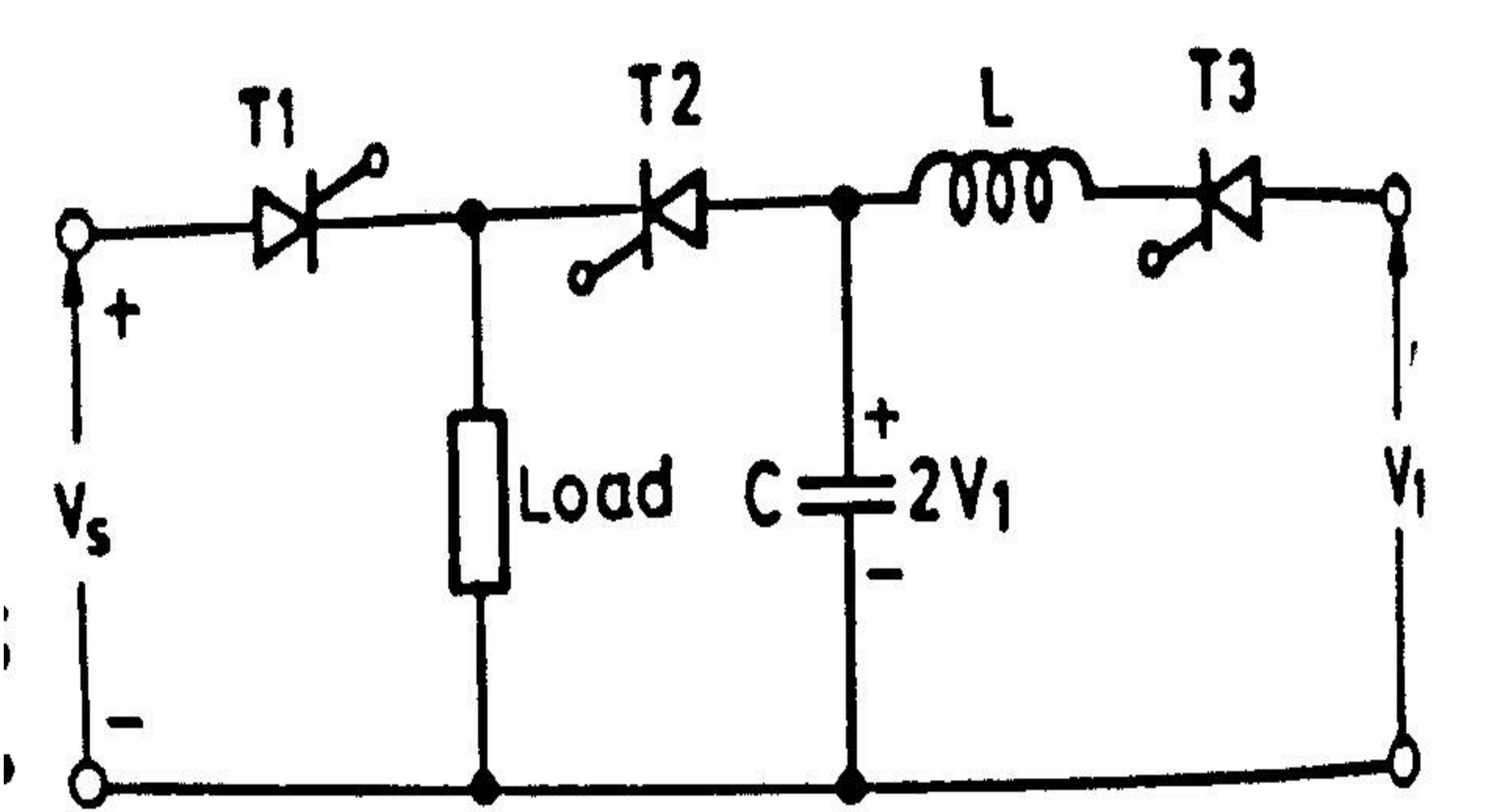
Class D, L-C or C switched by an auxiliary SCR

- Class C can be converted to Class D if the load current is carried by only one of the SCR's, the other acting as an auxiliary turn-off SCR.
- The auxiliary SCR would have a resistor in its anode lead of say ten times the load resistance.
- SCRA must be triggered first in order to charge the upper terminal of the capacitor as positive.
- As soon as C is charged to the supply voltage, SCRA will turn off.

Class D, L-C or C switched by an auxiliary SCR

- If there is substantial inductance in the input lines, the capacitor may charge to voltages in excess of the supply voltage.
- This extra voltage would discharge through the diode-inductor-load circuit.
- When SCRM is triggered the current flows in two paths: Load current flows through the load and the commutating current flows through C- SCRM -L-D network.
- The charge on C is reversed and held at that level by the diode D.
- When SCRA is re-triggered, the voltage across C appears across SCRM via SCRA and SCRM is turned off.

Class E – External pulse commutation



Class E – External pulse commutation

- A pulse of current is obtained from a separate voltage source to turn off the conducting SCR
- The peak value of the current pulse must be more than the load current
- Vs is the voltage of main source and V1 is the voltage of auxiliary supply
- Thyristor T1 is conducting and load is connected to Vs
- When T3 is turned on, V1, T3, L and C form an auxiliary circuit
- Therefore C is charged to a voltage +2V1and auxiliary current falls to zero T3 gets commutated
- For turning off T1, T2 is turned on
- With T2 on, T1 is subjected to a reverse voltage, Vs-2V1 and T1 is therefore turned off
- After T1 turned off, capacitor discharges through load

Class F : Line commutation

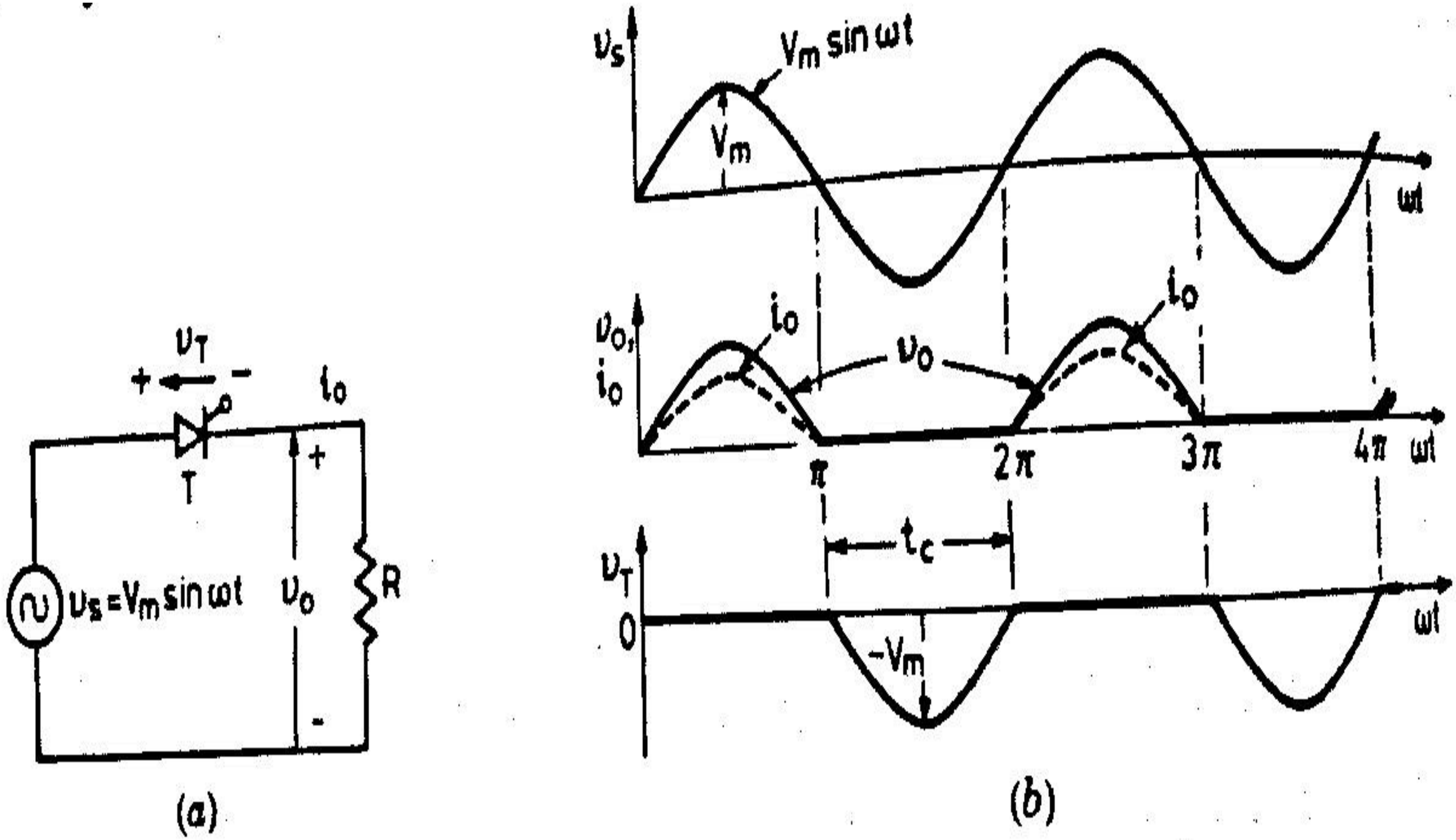


Fig. 5.7. Class F commutation (a) circuit diagram (b) waveforms.

Class F : Line commutation

- Can occur only when source is ac
- When SCR is energized from ac source, current has to pass through its natural zero at the end of every +ve half cycle
- Then ac source apply a reverse voltage across SCR automatically
- As a result SCR turned off
- This is called natural commutation, because no external circuit is employed to turn off the thyristor

Requirement of isolation and synchronization in gate drive circuit

- Electrical isolation is required between logic-level control signal and the drive circuit
- This is illustrated in case of a power BJT half-bridge converter having single phase ac as input where one of the power terminal is a grounded neutral wire
- The +ve dc bus is close to the ground potential during the -ve half cycle of Vs
- And the –ve dc bus is near ground potential during the +ve half cycle of Vs
- Under these conditions the emitter terminal of both BJTs must be treated as hot w.r.t power neutral
- The logic level control signals are normally referenced w.r.t logic ground, which is at the same potential as the power neutral since the logic circuits are connected to the neutral by means of a safety ground wire

Requirement of isolation and synchronization in gate drive circuit

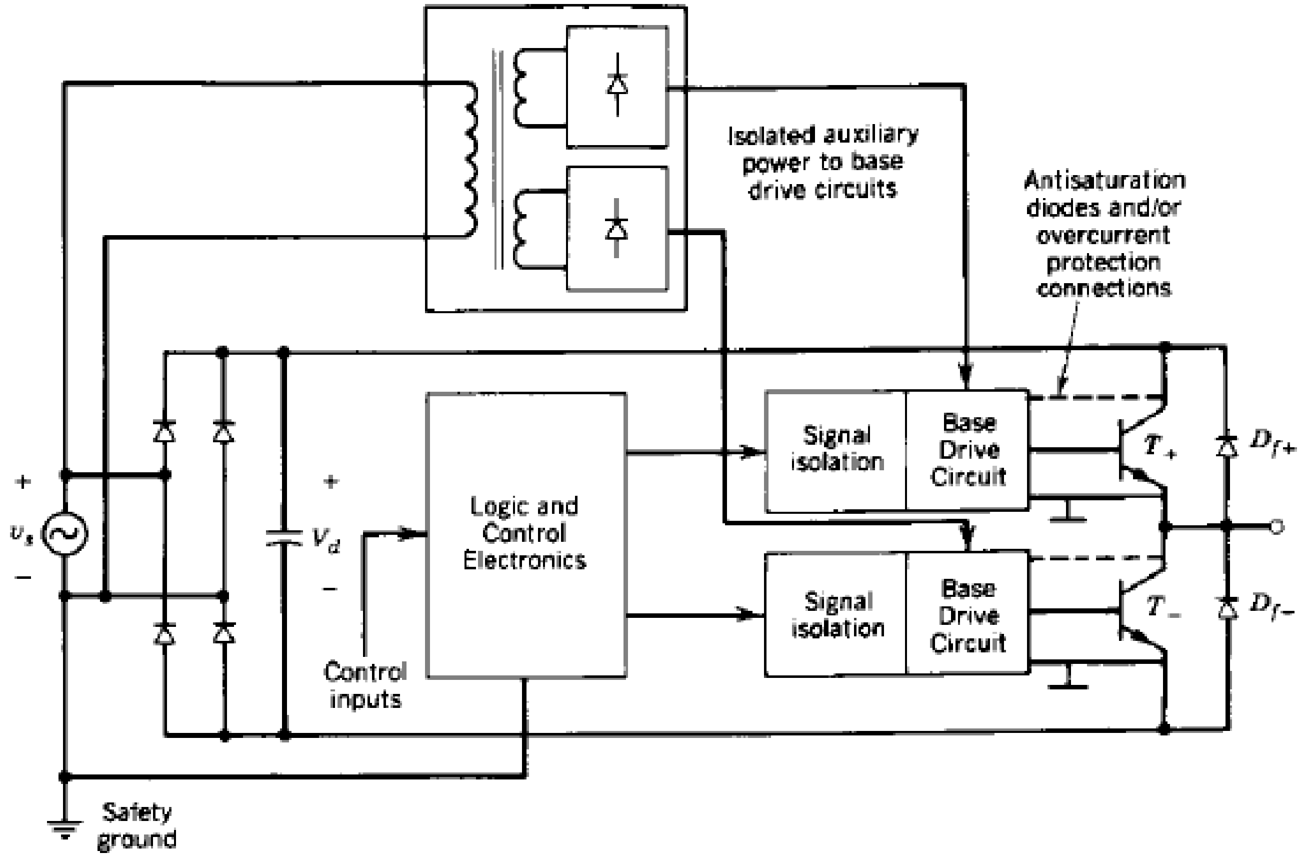


Figure 28-7 Power BJT base drive system showing the need for electrical isolation between the base drive circuitry and the logic level control circuitry.

Requirement of isolation and synchronization in gate drive circuit

The basic way to provide electrical isolation are either by

- Opto-coupler
- Fiber optics or by
- Transformer

Optocouplers

- Consist of a light emitting diode (LED), the output transistor and a built in schmitt trigger
- A +ve signal from the control logic causes the LED to emit light that is focused on the optically sensitive base region of a photo transistor

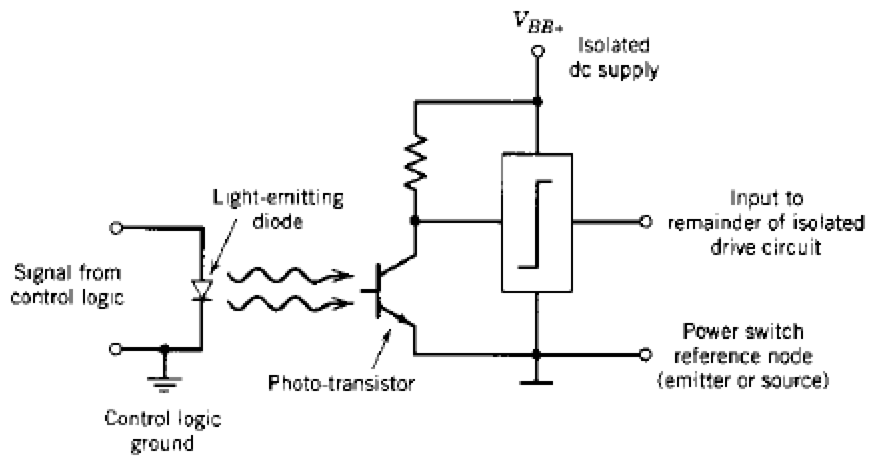


Figure 28-8 Schematic of an optocoupler used to couple signals to a floating (electrically isolated) drive circuit from a control circuit referenced with respect to the control logic ground (and power system neutral).

Optocouplers

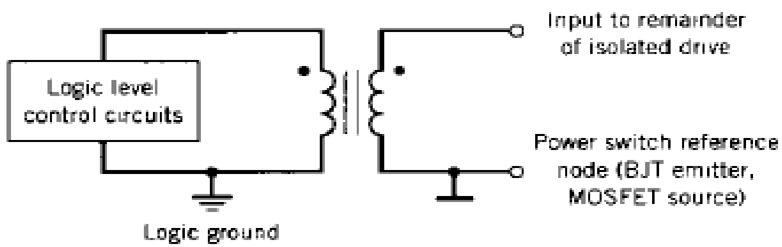
- The light falling on the base region generate a significant number of electron hole pair in the base region that causes the photo transistor to turn on
- The resulting drop in voltage at the photo transistor collector causes the schmitt trigger to change state
- The output of the schmitt trigger is the optocoupler output and can be used as the control input to the isolated drive circuit
- The capacitance between LED and the base of the receiving transistor within the optocoupler should be as small as possible to avoid retriggering at both turn on and turn off of the power transistor due to the jump in the potential between the power transistor emitter reference point and the ground of the control electronics

Optocouplers

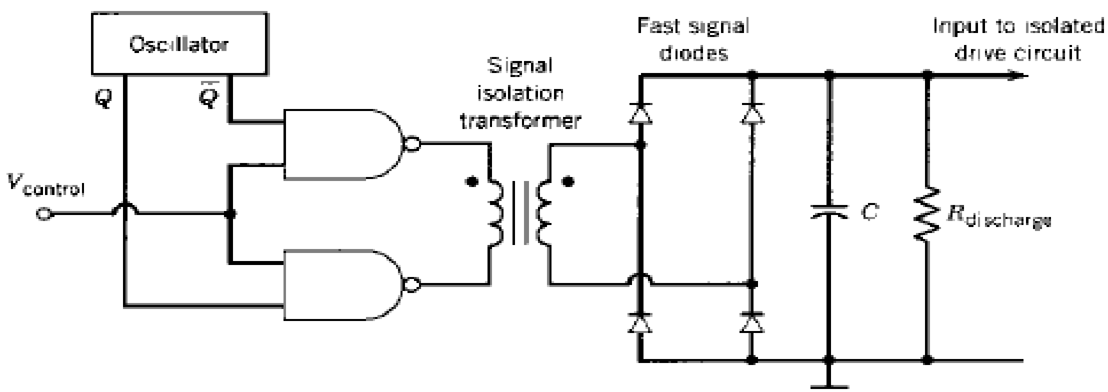
- To reduce this problem optocouplers with electrical shield between the LED and the receiver transistor should be used
- As an alternative, fiber optic cables can be used to completely eliminate this retriggering problem and to provide very high electrical isolation and creepage distance
- When using fiber optic cables, the LED is kept on the printed circuit board of the control electronics, and the optical fiber transmits the signal to the receiver transistor which is put on the drive circuit printed circuit board

Pulse transformer

- Instead of using optocouplers or fiber optic cables, the control signal can be coupled to the electrically isolated drive circuit by means of a transformer



(a)



(b)

Pulse transformer

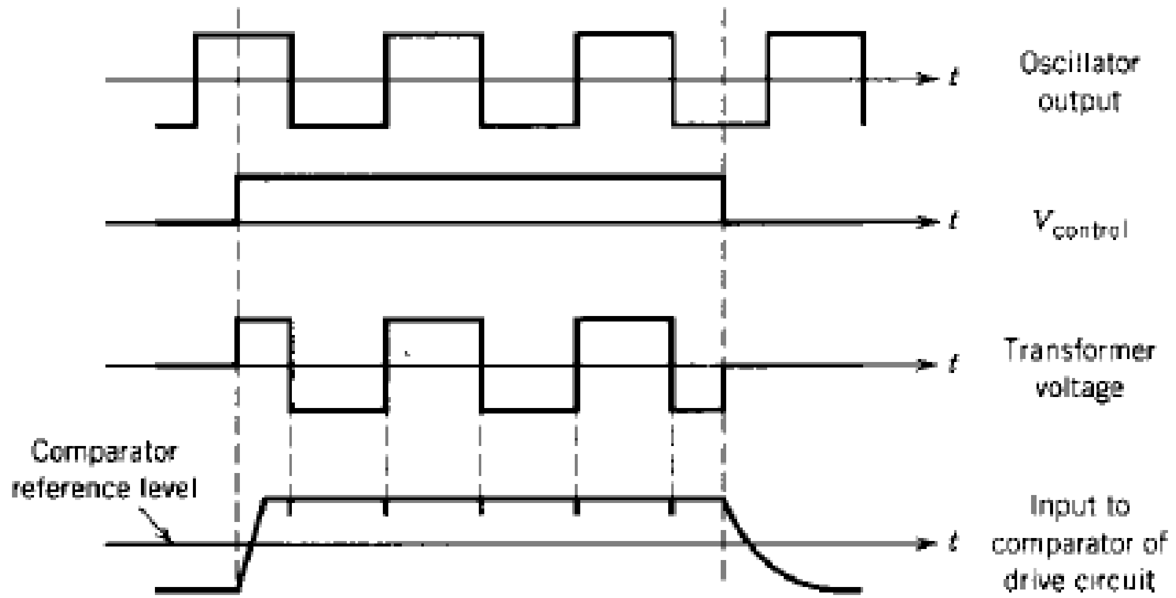


Figure 28-9 Transformer coupling of control signals from control circuits to electrically isolated drive circuits. In (*a*) the baseband control signal is directly connected to the transformer primary. In (*b*) the control signal modulates a high-frequency carrier that is then applied to the primary of a small high-frequency signal transformer. The waveforms associated with (*b*) are shown in (*c*).

Pulse transformer

- If the switching frequency is high and the duty ratio D varies only slightly around 0.5, a baseband control signal of appropriate magnitude can be applied directly to the primary of a relatively small and light weight pulse transformer as in (a)
- And the secondary output can be used to either directly drive the power switch or used as the input to an isolated drive circuit
- As the switching frequency is decreased below the tens of kilohertz range, a baseband control signal directly applied to the transformer primary becomes impractical because the size and weight of the transformer becomes increasingly larger

Pulse transformer

- Modulation of a high frequency carrier by a low frequency control signal enables a small high frequency pulse transformer to be used for even low frequency control signal
- In fig.b. the control signal modulates a high frequency oscillator output before being applied to the primary of a high frequency signal transformer
- Since a high frequency transformer can be made quite small, it is easy to avoid stray capacitance between the input and output winding and the transformer will be inexpensive
- The transformer secondary output is rectified and filtered and then applied to the comparator and the rest of the isolated drive circuit

Controlled rectifiers – Principles of phase control

- the firing angle may defined as the angle between the instant thyristor would conduct if it were a diode and the instant it is triggered
- Is measured form the angle that gives the largest average output voltage or the highest load voltage
- It is also defined as the angle measured from the instant that gives the largest output voltage to the instant it is triggered
- Angle measured from the instant SCR gets forward biased to the instant it is triggered

Single phase half controlled

- Single phase half controlled rectifier with R load
- Single phase half controlled rectifier with R L load
- Single phase half controlled rectifier with R L load and freewheeling diode
- Single phase half controlled rectifier with R L E load
- Single phase half controlled rectifier with R L E load and freewheeling diode

Single phase full controlled

- Single phase full controlled rectifier with R load
- Single phase full controlled rectifier with R L load (Continues conduction)
- Single phase full controlled rectifier with R L load (Discontinues conduction)
- Single phase full controlled rectifier with R L load and freewheeling diode
- Single phase full controlled rectifier with R L E load (Continues conduction)
- Single phase full controlled rectifier with R L E load (Discontinues conduction)
- Single phase full controlled rectifier with R L E load and freewheeling diode

Single phase semi converter

- Single phase semi-converter with R load
- Single phase semi-converter with R L load (Continues conduction)
- Single phase semi-converter with R L load (Discontinues conduction)
- Single phase semi-converter with R L load and freewheeling diode
- Single phase semi-converter with R L E load (Continues conduction)
- Single phase semi-converter with R L E load (Discontinues conduction)
- Single phase semi-converter with R L E load and freewheeling diode

Single phase half wave circuit with R load

- The source voltage is $v_s = V_m \sin \omega t$
- An SCR can conduct only when anode voltage is +ve and a gate signal is applied
- At some delay angle α, a +ve gate signal applied between gate and cathode turns on the SCR
- Immediately full supply voltage is applied across the load
- At the instant of angle α, Vo rises from zero to $V_m \sin \omega t$
- Thyristor remains on from ωt=α to π, (2π+α) to 3π etc…
- During this interval voltage across thyristor =0
- I is off from π to (2π+α), 3π to (4π+α) etc…
- During this interval voltage across thyristor has the wave shape of supply voltage

Single phase half wave circuit with R load

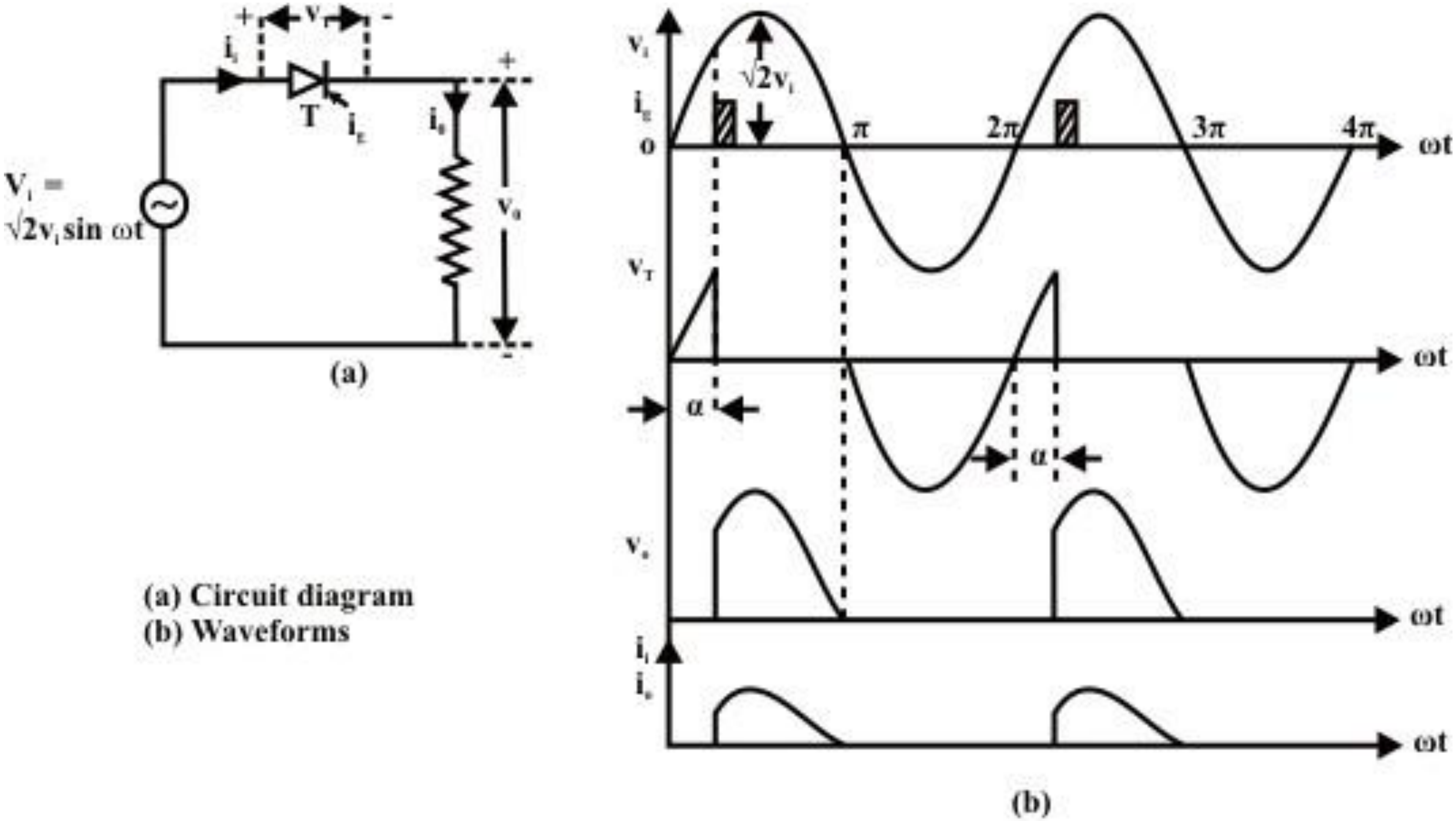


Fig. 10.1: Single phase fully controlled half wave rectifier supplying a resistive load

Single phase half wave circuit with R load

$It\ may\ be\ observed\ that\ v_s = v_o + v_T$

$As\ the\ thyristor\ is\ reverse\ biased\ for\ \pi\ radians, circuit\ turn\ off\ time$

$t_c = \frac{\pi}{\omega}, where\ \omega = 2\pi f\ and\ f\ is\ the\ supply\ frequency$

$Average\ voltage\ across\ load\ R\ is\ given\ by$

$$V_o = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{2\pi}(1+\cos\alpha)$$

$The\ maximum\ value\ of\ average\ output\ voltage\ occurs\ at\ \alpha = 0$

$$V_{o.m} = \frac{V_m}{2\pi}.2 = \frac{V_m}{\pi} \qquad Also, V_o = \frac{V_{o.m}}{2}(1+\cos\alpha)$$

Single phase half wave circuit with R load

$$Average\,load\,current, I_o = \frac{V_o}{R} = \frac{V_m}{2\pi R}(1+\cos\alpha)$$

- R.m.s. value of voltage is given by

$$V_{or} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m{}^2 \sin^2\omega t . d(\omega t)\right]^{1/2}$$

$$= \frac{V_m}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]^{1/2}$$

- The value of r.m.s current is

$$I_{or} = \frac{V_{or}}{R}$$

Single phase half wave circuit with R load

- Power delivered to resistive load = (rms load voltage)(rms load current) $= V_{or} I_{or} = \dfrac{V_{or}^{\;2}}{R} = I_{or}^{\;2} R$

- Input volt amperes = (rms source voltage) (total rms line current)

$$= V_s I_{or} = \frac{V_s^{\;2}\sqrt{2}}{2R\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right]^{1/2}$$

- Input power factor

$$= \frac{power\ delivered\ to\ the\ load}{input\ VA} = \frac{V_{or} I_{or}}{V_s I_{or}} = \frac{V_{or}}{V_s}$$

$$pf = \frac{1}{\sqrt{2\pi}}\left[(\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right]^{1/2}$$

Single phase half wave circuit with RL load

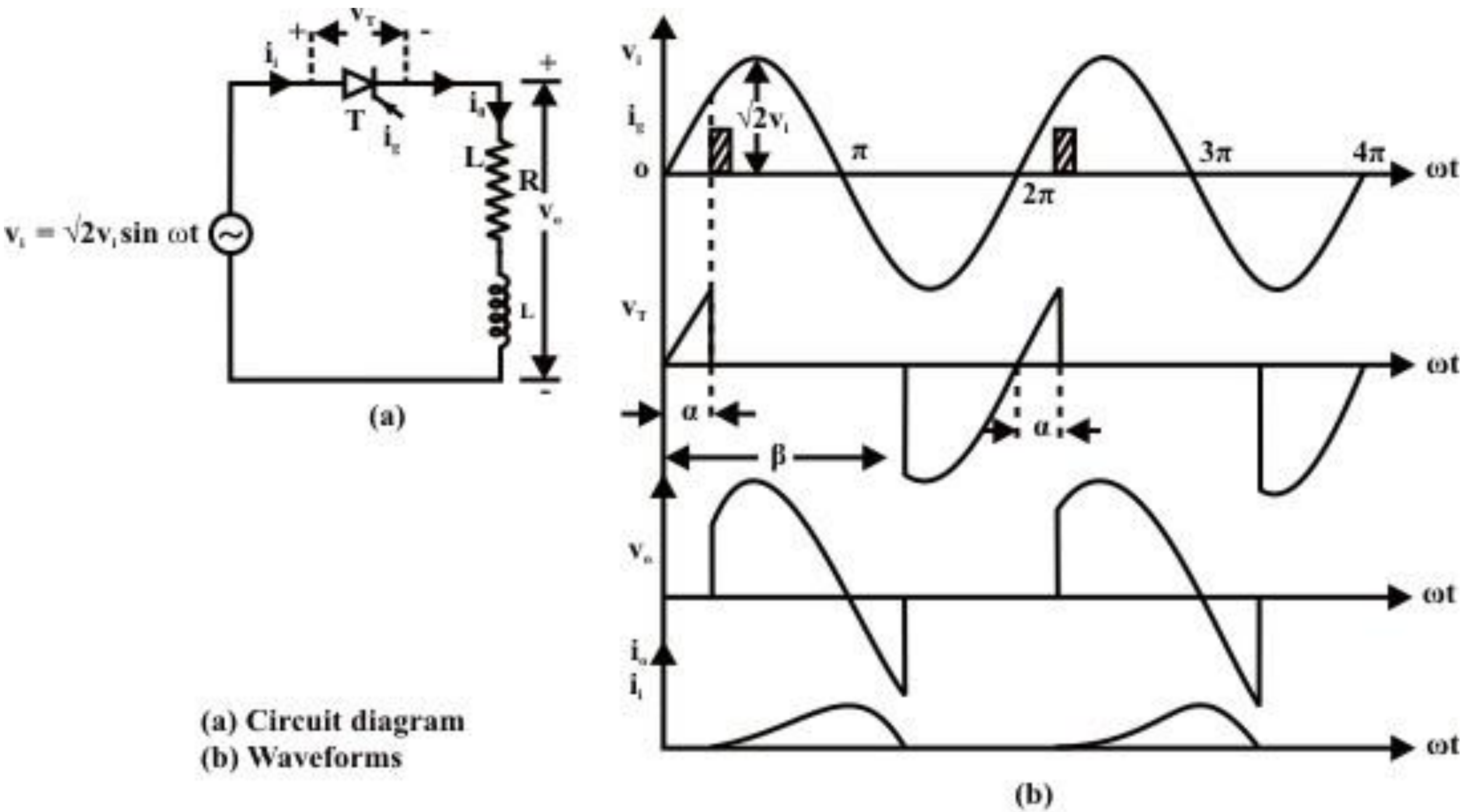


Fig. 10.2: Single phase fully controlled half wave rectifier supplying a resistive inductive load

Single phase half wave circuit with RL load

- At $\omega t=\alpha$ thyristor is turned on by gate signal
- The load voltage Vo at once become equal to the source voltage Vs
- But the inductance L forced the load, or output current io to rise gradually
- After some time io reaches maximum value and then begin to decrease
- At $\omega t=\pi$, Vo is zero but io is not zero because of the load inductance
- After $\omega t=\pi$, SCR is subjected to reverse anode voltage but it will not be turned off as load current io is not less than holding current
- At some angle $\beta>\pi$, io reduces to zero and SCR is turned off as it is already reverse biased

Single phase half wave circuit with RL load

- After $\omega t=\beta$, vo=0 and io=0
- At $\omega t=2\pi+\alpha$, SCR is triggered again, vo is applied to the load and load current develops as before
- Angle is called the extinction angle and is called the conduction angle
- The circuit turn off time $t_c = \dfrac{2\pi - \beta}{\omega}$
- The voltage equation for the circuit when T is on

$$V_m \sin \omega t = R i_o + L \frac{di}{dt}$$

Single phase half wave circuit with RL load

- Average load voltage

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$$

- Average load current

$$I_o = \frac{V_m}{2\pi R}(\cos\alpha - \cos\beta)$$

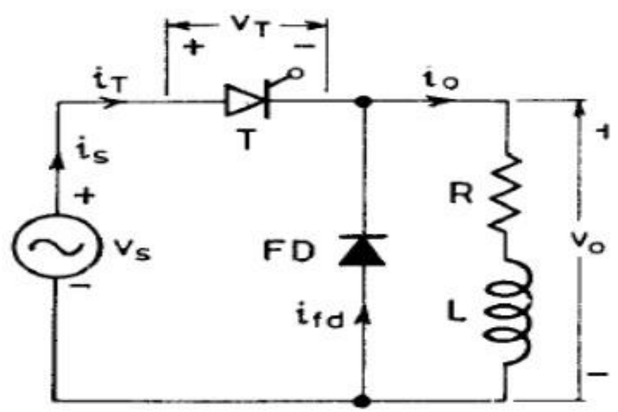
- Rms load voltage

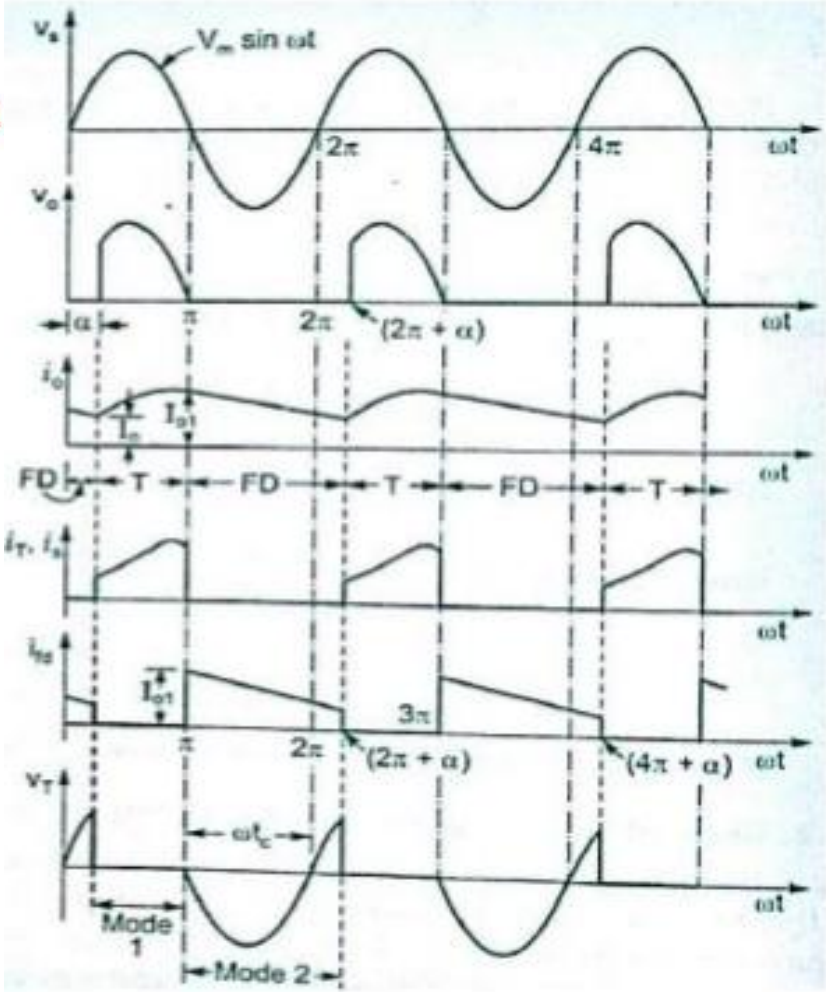
$$V_{or} = \left[\frac{1}{2\pi}\int_{\alpha}^{\beta} {V_m}^2 \sin^2\omega t.\, d(\omega t)\right]^{1/2}$$

$$= \frac{V_m}{2\sqrt{\pi}}\left[(\beta - \alpha) - \frac{1}{2}\{\sin 2\beta - \sin 2\alpha\}\right]^{1/2}$$

Single phase half wave circuit with RL load and freewheeling diode

Single phase Half wave Control with
R-L load & Free Wheeling Diode





Single phase half wave circuit with RL load and freewheeling diode

- The waveform of load current io can be improved by connecting a freewheeling diode across the load
- A freewheeling diode is also called bypass diode or commutating diode
- At $\omega t=0$, source voltage becoming +ve
- At some delay angle α, forward biased SCR is triggered and source voltage Vs appears across the load as Vo
- At $\omega t=\pi$, source voltage Vs=0, and just after this instant as Vs tends to reverse freewheeling diode FD is forward biased through the conducting SCR
- As a result load current io is immediately transferred from SCR to FD as Vs tends to reverse

Single phase half wave circuit with RL load and freewheeling diode

- At the same time SCR is subjected to reverse voltage and zero current, it is therefore turned off at $\omega t=\pi$
- It is assumed that during freewheeling period, load current does not decays to zero until the SCR is triggered again at $(2\pi+\alpha)$
- Voltage drop across FD is taken as almost zero, the load voltage vo is therefore zero during the freewheeling period
- SCR is reverse biased from $\omega t=\pi$ to $\omega t=2\pi$
- Therefore circuit turn off time

$$t_c = \frac{\pi}{\omega}$$

Single phase half wave circuit with RL load and freewheeling diode

- Operation of the circuit can be explained in two modes
- *First mode – conduction mode*
- SCR conduct from α to π, 2π+α to 3π and so on and FD is reverse biased
- The duration of this mode is for [(π-α)/ω] sec
- For conduction mode the voltage equation be

$$V_m \sin \omega t = R i_o + L \frac{d i_o}{dt}$$

- *Mode II – freewheeling mode*
- Π to 2π+α, 3π to 4π+α etc...
- In this mode SCR is reverse biased from Π to 2π, 3π to 4π etc...

Single phase half wave circuit with RL load and freewheeling diode

- As the load current is assume continues, FD conducts from Π to 2π+α, 3π to 4π+α etc... and so on
- The voltage equation for this mode

$$0 = Ri_o + L\frac{di_o}{dt}$$

- Average load voltage is given by

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.d(\omega t) = \frac{V_m}{2\pi}(1+\cos\alpha)$$

- Average load current

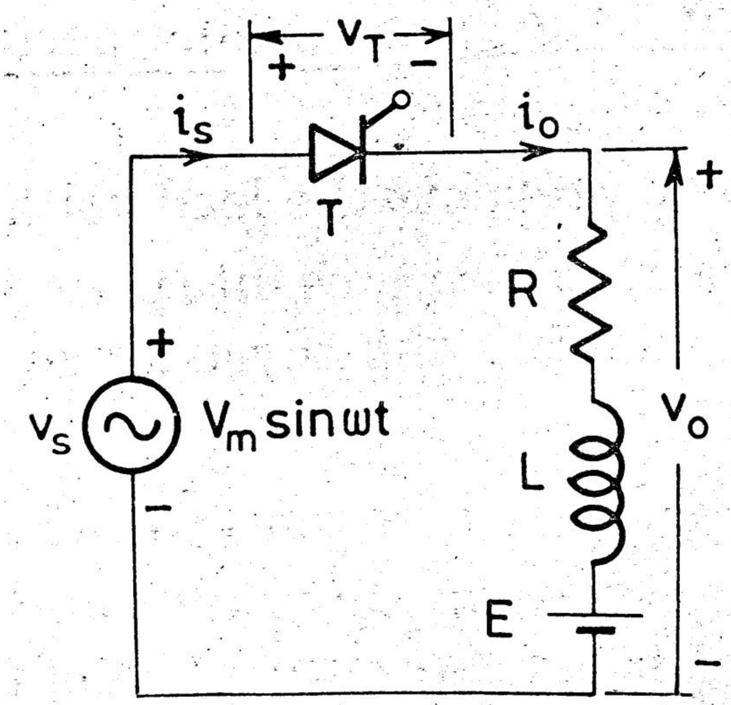
$$I_o = \frac{V_0}{R} = \frac{V_m}{2\pi R}(1+\cos\alpha)$$

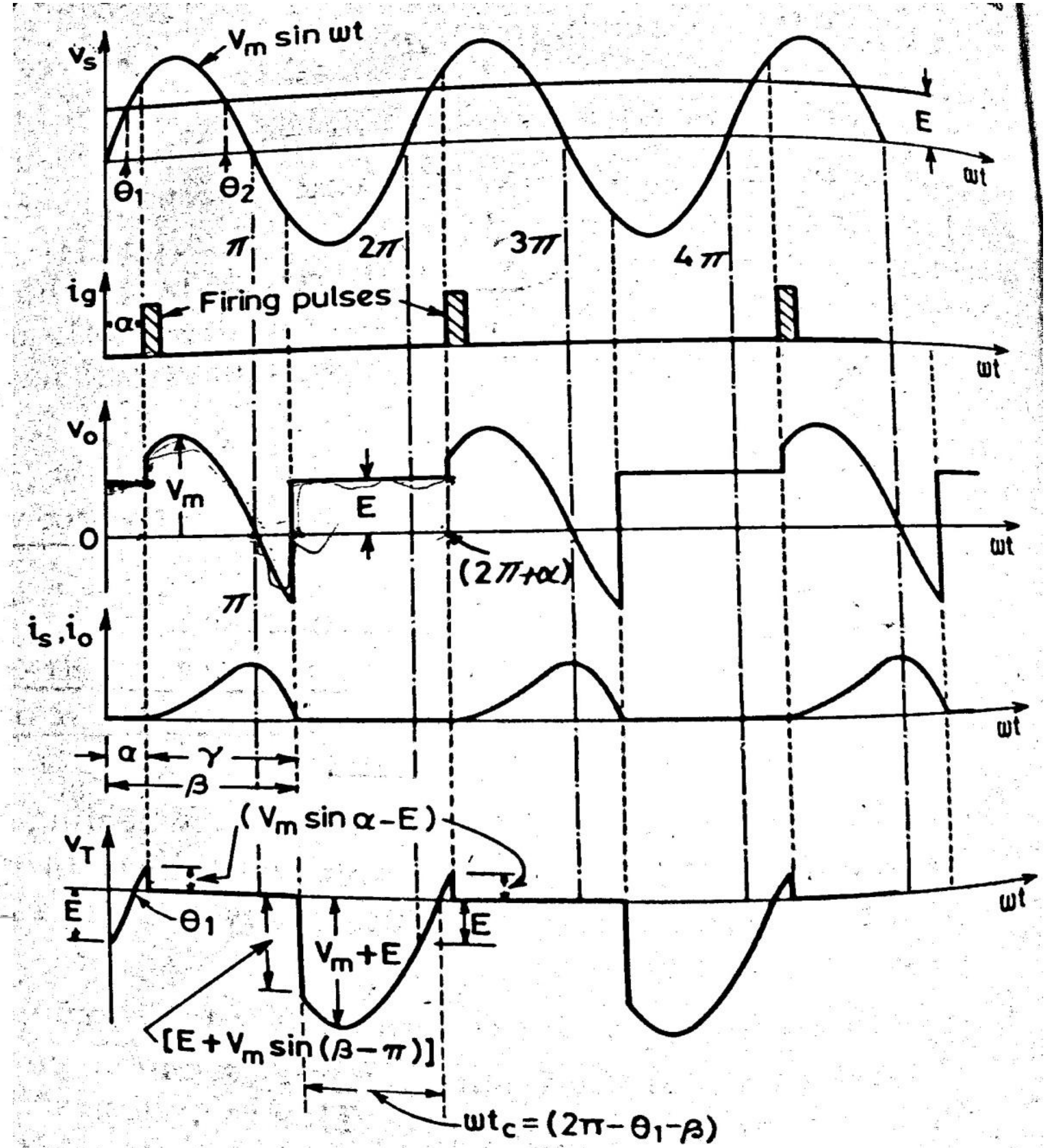
Single phase half wave circuit with RL load and freewheeling diode

The advantages of using FD are

- Input pf is improved
- Load current waveform is improved
- Load performance is better
- As energy is stored in the inductor L is transferred to R during the freewheeling period overall converter efficiency improves

Single phase half wave circuit with RLE load





Single phase half wave circuit with RLE load

- The counter emf in the load may be due to battery or dc motor
- The minimum value of firing angle is obtained form the relation $V_m \sin \omega t = E$
- This is occur at an angle $\theta_1 = \sin^{-1}\left(E/V_m\right)$
- In case thyristor T is fired at an angle $\alpha<\theta_1$, then E>Vs, SCR is reverse biased and therefore it will not turn on
- Similarly maximum value of firing angle is $\theta_2=\pi-\theta_1$
- During the interval load current is zero and load voltage V0=E
- And during the time io not zero, vo follows vs

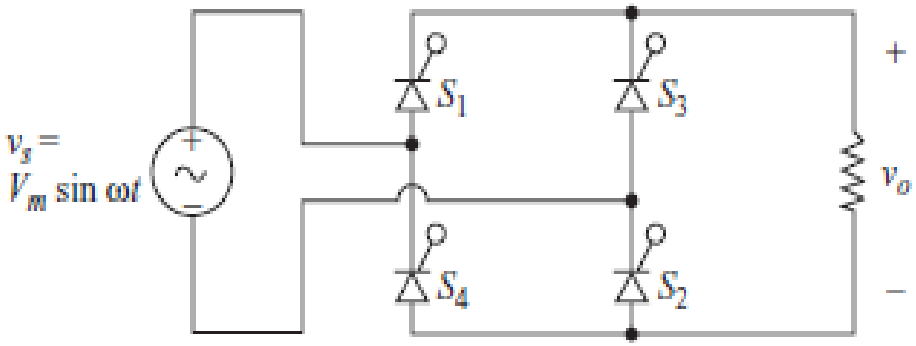
Single phase half wave circuit with RLE load

- Voltage equation $V_m \sin \omega t = R i_o + L \frac{di_o}{dt} + E$
- $$V_0 = \frac{1}{2\pi} \int_{\alpha}^{\beta} V_m \sin \omega t . d(\omega t) + E(2\pi + \alpha - \beta)$$

$$= \frac{1}{2\pi} [V_m(\cos \alpha - \cos \beta) + E(2\pi + \alpha - \beta)]$$

- Average load current $I_o = \frac{1}{2\pi R} [V_m(\cos \alpha + \cos \theta_1) - E(\pi - (\theta_1 + \alpha))]$

Single phase fully controlled bridge rectifier with R load



Single phase fully controlled bridge rectifier with R load

- The output voltage waveform for a controlled full-wave rectifier with a resistive load is shown in Fig.
- The average component of this waveform is determined from

$$\boxed{V_o = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)\, d(\omega t) = \frac{V_m}{\pi}(1 + \cos\alpha)}$$

- Average output current

$$I_o = \frac{V_o}{R} = \frac{V_m}{\pi R}(1 + \cos\alpha)$$

- Rms value of output voltage

$$V_{or} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} {V_m}^2 \sin^2\omega t.\, d(\omega t)\right]^{1/2} = \left[\frac{{V_m}^2}{2\pi}[(\pi - \alpha) + (1 + \cos 2\alpha)]\right]^{1/2}$$

Single phase fully controlled bridge rectifier with R load

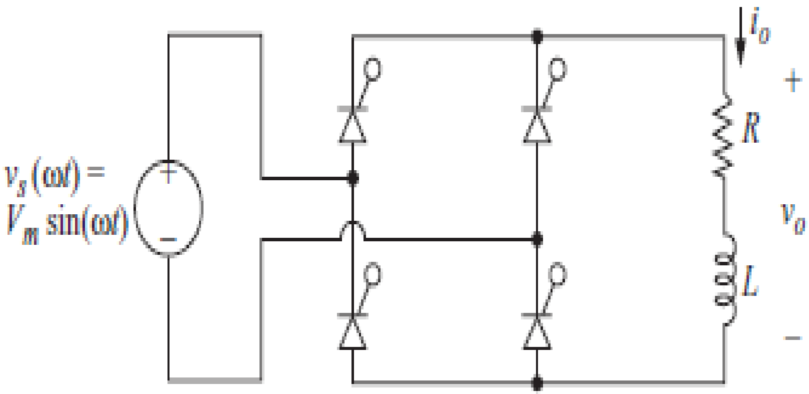
- The power delivered to the load is a function of the input voltage, the delay angle, and the load components; *P =I^2* rms *R is used to determine the power in a* resistive load, where

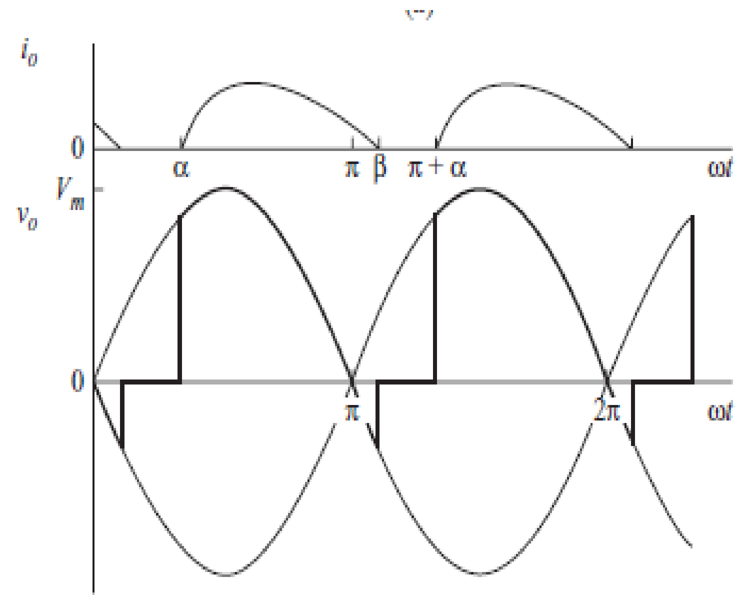
$$I_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\frac{V_m}{R}\sin\omega t\right)^2 d(\omega t)}$$

$$= \frac{V_m}{R}\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\sin(2\alpha)}{4\pi}}$$

Single phase fully controlled bridge rectifier with RL load

Discontinues conduction





Single phase fully controlled bridge rectifier with RL load

Discontinues conduction

- Load current for a controlled full-wave rectifier with an RL load can be either continuous or discontinuous, and a separate analysis is required for each.
- Starting the analysis at $\omega t = 0$ with zero load current, SCRs S1 and S2 in the bridge rectifier will be forward-biased and S3 and S4 will be reverse-biased as the source voltage becomes positive.
- Gate signals are applied to S1 and S2 at $\omega t=\alpha$,turning S1 and S2 on.
- With S1 and S2 on, the load voltage is equal to the source voltage.

Single phase fully controlled bridge rectifier with RL load

Discontinues conduction

- Current function

$$i_o(\omega t) = \frac{V_m}{Z}\left[\sin(\omega t - \theta) - \sin(\alpha - \theta)\, e^{-(\omega t - \alpha)/\omega\tau}\right] \qquad \text{for } \alpha \le \omega t \le \beta$$

where (4-26)

$$Z = \sqrt{R^2 + (\omega L)^2} \qquad \theta = \tan^{-1}\left(\frac{\omega L}{R}\right) \qquad \text{and} \qquad \tau = \frac{L}{R}$$

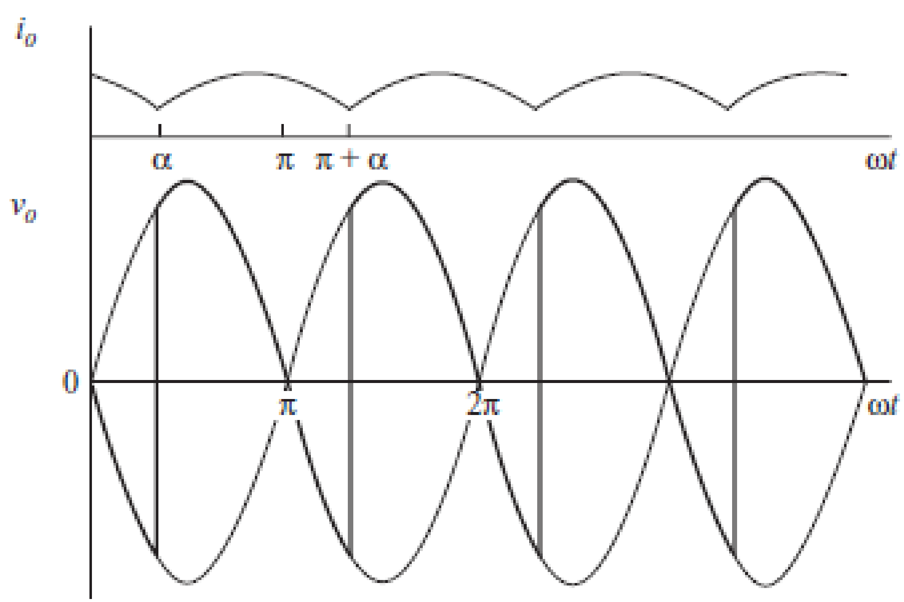
- The above current function becomes zero at $\omega t = \beta$.
- If $\beta < \pi + \alpha$, the current remains at zero until $\omega t = \pi + \alpha$, when gate signals are applied to S3 and S4 which are then forward-biased and begin to conduct.
- This mode of operation is called discontinuous current, which is illustrated in Fig. b.

$$\beta < \alpha + \pi \quad \rightarrow \quad \text{discontinuous current}$$

Single phase fully controlled bridge rectifier with RL load

Continues conduction

- If the load current is still positive at ωt=π+α, when gate signals are applied to S3 and S4 in the above analysis, S3 and S4 are turned on and S1 and S2 are forced off



Single phase fully controlled bridge rectifier with RL load

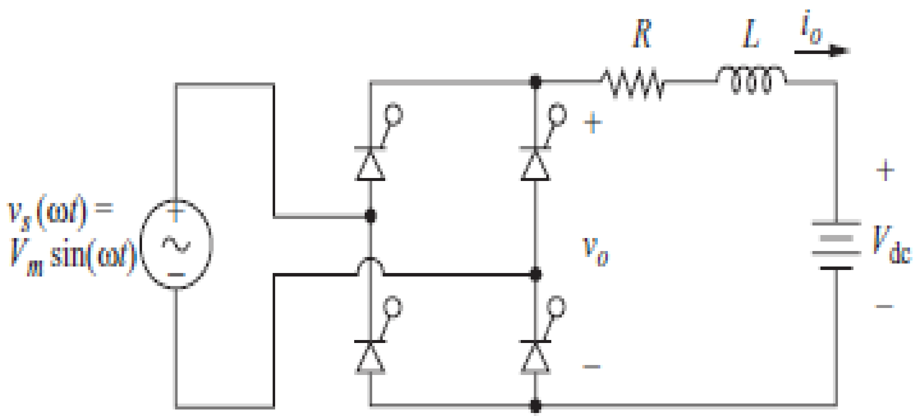
- Average output voltage

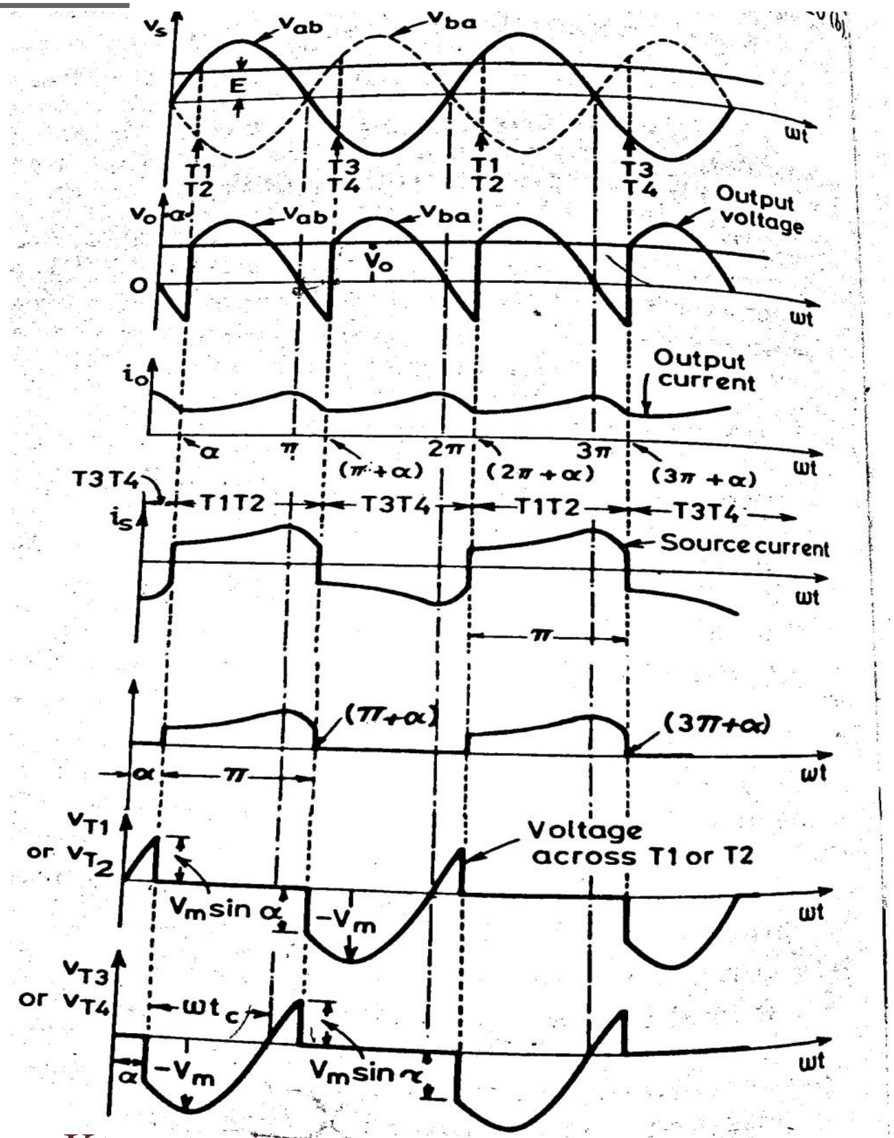
$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t . d(\omega t) = \frac{2V_m}{\pi}(\cos\alpha)$$

- Rms value of voltage

$$V_{or} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m{}^2 \sin^2\omega t . d(\omega t)\right]^{1/2}$$

Single phase fully controlled bridge rectifier with RLE load





Single phase fully controlled bridge rectifier with RLE load (Continues conduction)

- Average value of output voltage is given by

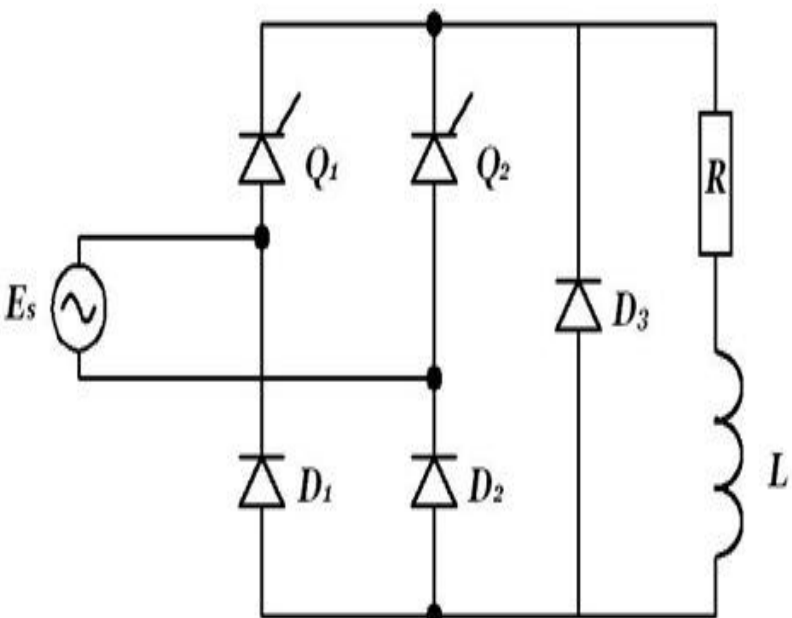
$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t.\,d(\omega t) = \frac{2V_m}{\pi}(\cos\alpha)$$

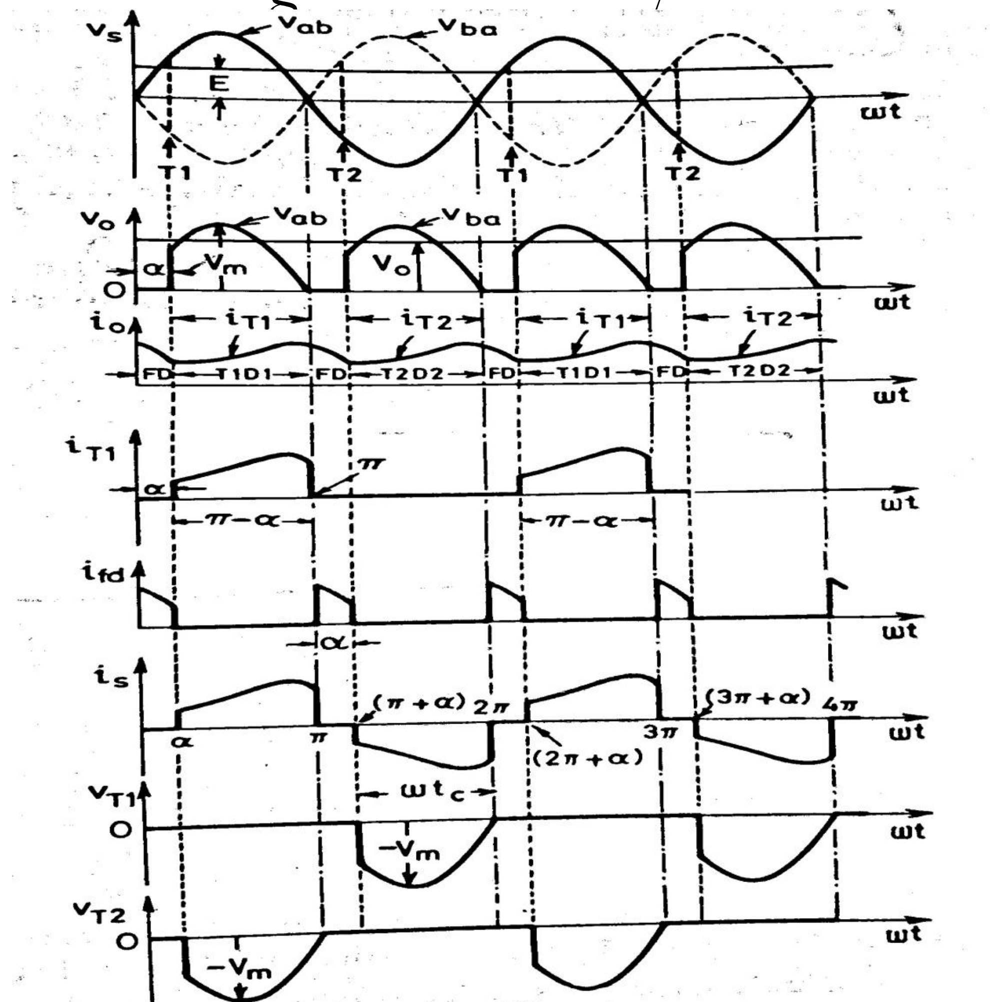
- Rms value (*square root of)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} {V_m}^2 \sin^2\omega t.\,d(\omega t) = \frac{{V_m}^2}{\pi}\left[\omega t - \frac{1}{2}|\sin 2\omega t|_{\alpha}^{\pi+\alpha}\right] = \frac{{V_m}^2}{2}$$

Single phase semi converter

- A single phase semi converter bridge with two thyristor and three diodes are shown





Single phase semi converter

- The two thyristor are T1 and T2, and the two diode D1, D2 and third diode is connected across load as free wheeling diode
- The load is of RLE type
- After $\omega t=0$, thyristor T1 is forward biased only when source voltage exceeds E
- Thus T1 is triggered at a firing angle α, such that Vm sinα >E
- With T1 on load get connected to source through T1 and D1
- For the period $\omega t= \alpha$ to π, load current io flows through RLE load, D1, source and T1
- And the load terminal voltage is same as source voltage

Single phase semi converter

- Soon after $\omega t=\pi$, load voltage Vo tends to reverse as the ac source voltage changes polarity
- Just as Vo tends to reverse, FD gets forward biased and starts conducting
- The load or output current io is transferred from T1, D1 to FD
- As T1 is reverse biased at $\omega t=\pi+$ through FD, T1 is turned off at $\omega t=\pi+$
- The load terminal are short circuited through FD therefore load or output voltage is zero during $\pi< \omega t< \pi+\alpha$
- After $\omega t= \pi$, during –ve half cycle, T2 will be forward biased only when the source voltage is more than E

Single phase semi converter

- Semi converter with R load

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$$

- Semi converter with RL load (continues conduction)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t.\, d(\omega t) = \frac{2V_m}{\pi}(\cos\alpha)$$

- Semi converter with RL load and free wheeling diode

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$$

Single phase semi converter

- Semi converter with RLE load (continues conduction)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t.\, d(\omega t) = \frac{2V_m}{\pi}(\cos\alpha)$$

- Semi converter with RLE load and free wheeling diode

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$$